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PILOTED FLIGHT SIMULATION STUDY OF LOW-LEVEL WIND SHEAR, PHASE 4

ALL-WEATHER LANDING SYSTEMS, ENGINEERING SERVICES SUPPORT PROJECT, TASK 2

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Interim Report

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16. Abstract

This report describes the fourth in a series of piloted DC-10 flight simulation exercises concerned with the development and test of airborne techniques designed to aid the pilot in detecting and coping with low-level wind shear. The exercise included validation tests of systems developed from the techniques that had shown the most promise in previous tests.

Two approach-and-landing situations were simulated, using manual control assisted by flight director. The first was a precision (full ILS) approach in Category I visibility to an 11,500-foot runway at 5300-foot field elevation, 95° temperature. The systems tested were MFD/ΔA (modified steering and thrust commands on flight director, acceleration margin for go-around advisory, and modified go-around steering command) and GNS/RED (dual-pointer display of airspeed and ground speed with compatible thrust command, alphanumeric microcomputer display for go-around, and modified go-around steering command). The second situation was a non-precision approach (localizer only) with 400-foot ceiling, 5000-foot RVR, to the same runway. The systems tested were MFD/ΔA and GNS/MF/R (same as GNS/RED except for modified flight director steering), both using a synthetic glide path. Each test involved 10 subject pilots and 10 wind profiles, 3 for training and 7 for test. Performance of both aiding systems was better than baseline (conventional) approach management, and the MFD/ΔA was good enough to constitute a solution.

In a third test, takeoff trials were run against 5 wind profiles by the 3 project pilots. No good airborne means of coping with wind shear was found.

This work was accomplished by the AWLS team (SRI, Bunker Ramo Corporation, and Collins Avionics Group) with Douglas Aircraft Company as simulation subcontractor.

17. Key Words
Wind shear
DC-10 flight simulation
Ground speed
Go-around aids
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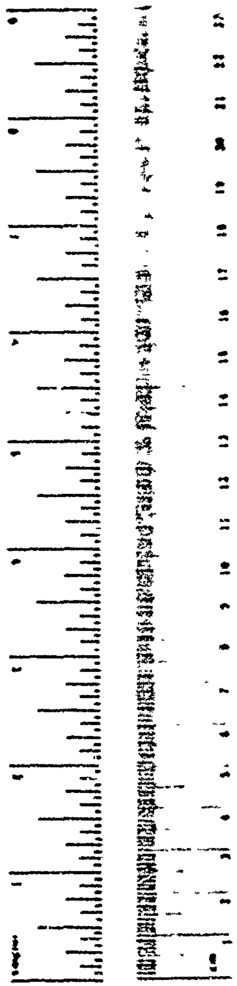
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

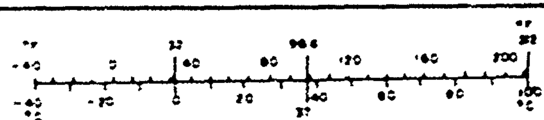
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



PREFACE

The purpose of Task 2 of the All-Weather Landing Systems (AWLS) project is to develop and implement a manned flight simulation program to (1) investigate terminal flight operations, emphasizing wind shear effects, and (2) determine the operational and technical role of head-up displays. This interim report describes the results obtained by the AWLS team--SRI, Bunker Ramo Corporation, and Collins Avionics Group of Rockwell International--on a validation test with a DC-10-10 aircraft simulator of the capabilities of certain aiding concepts to assist the pilot in coping with low-level wind shear. The aids were based on airborne instrumentation, and the information was displayed on the instrument panel. The aiding systems tested included approach management techniques, go-around decision aids, and techniques for assisting the pilot during the go-around maneuver. The sponsoring organizations are FAA Wind Shear Program Office and ARD-740; the Technical Monitor is W. J. Cox.

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I INTRODUCTION

A. Program and Objectives

The FAA Wind Shear Program has the objectives of examining the hazards associated with low-level wind shear, developing solutions to the wind-shear problem, implementing the solutions, and integrating them into the National Airspace System. In support of this program, potential solutions in the category of airborne equipment are being investigated by the All-Weather Landing Systems (AWLS) team under Task 2 of a contract from the FAA Approach and Landing Division. The Task 2 team consists of SRI, Bunker Ramo Corporation (BR), and Collins Avionics Group of Rockwell International.

The investigation has been concerned with airline transport jet aircraft. The approach has been to give primary consideration to the lowest-cost candidate aiding concepts to ensure that any potential solution will be cost effective. The project task has included the design and test of airplane control laws, the analysis of airplane responses to wind shears, the development of wind models, the determination of the hazards presented by various wind fields, and the development and test of various instruments intended to aid the pilot in coping with wind shear. The majority of the effort has been spent on a series of piloted flight simulation tests. Table 1 summarizes these simulation exercises that have been sponsored under the FAA Wind Shear Program. Except for the most recent, these tests have formally treated only the precision-approach problem--i.e., approach and landing with full Instrument Landing System (ILS). The first tests,[1*] were exploratory in nature; a DC-10 training simulator was supplied and supported by Douglas Aircraft Company, McDonnell-Douglas Corporation, under subcontract. A similar

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*References are listed at the end of this report.

Table 1

SUMMARY OF WIND-SHEAR PILOTED FLIGHT SIMULATION TESTS

Period	Test Conductor	Aircraft	Simulator	Number of Wind Profiles	Number of Pilots
Apr-May 1976	SRI, BR	DC-10	Douglas, Training	4	8
July 1976	FAA ARD-540	B-737	NASA, FSAA	3	11
Nov 1976-Jan 1977	SRI, BR	DC-10	Douglas, MBDFS	4	16
July-Aug 1977	SRI, BR, ARD-540	B-727	NASA, FSAA	12	7
Sept-Oct 1977	SRI, BR	DC-10	Douglas, MBDFS	8	8+26
Nov 1978-Jan 1979	SRI, BR	DC-10	Douglas, MBDFS	15	20

exploratory study was conducted with a B-737 model in the Flight Simulator for Advanced Aircraft (FSAA) at the National Aeronautics and Space Administration's Ames Research Center. The aiding techniques showing the most promise and potential cost effectiveness were tested in the Phase 2 exercise[2] with a DC-10 model in the Douglas Moving-Base Development Flight Simulator (MBDFS). In Autum of 1977 a Phase 3 test of DC-10 aiding techniques was conducted in the Douglas MBDFS. This involved a set of wind profiles significantly expanded over those used in earlier DC-10 tests. Eight pilots took part in initial trials of candidate aiding techniques, and an especially large group (26) of subject pilots participated in a "Full Trial" of the three most promising systems; in these trials an aiding "system" incorporated ground speed information, flight steering guidance, a thrust control function and an automatic warning (or advisory) that a go-around should be initiated. The overall performance was marginal; it would have been adequate if the subject pilots had always chosen to honor the go-around advisories. However, the rate of nuisance alarms on the go-around warning was too high. Improvement of the go-around decision aids was needed.[3]

The most recent exercise was the Phase 4 test of aiding systems. It has just been completed at Douglas in the DC-10 MBDFS and is the subject of this report.

B. Test Outline

The major purpose of the DC-10 Phase 4 test was to measure the effectiveness of the best wind-shear aiding concepts. The goal, of course, was to show that there exists a cost-effective airborne system that will solve the wind-shear problem.

The aiding concepts considered were those that had shown the most promise in earlier trials. They were refined and, in some cases, augmented to correct the deficiencies that had been exposed. The scope of the tests was extended to include takeoffs and non-precision approaches--i.e., approach and landing with ILS localizer (LOC) but without a glideslope beam. Table 2 shows the specific aiding techniques considered

Table 2

AIDS AND SITUATIONS TESTED

Aid \ Situation	Precision Approach	Non-Precision Approach	Takeoff
Speed control: airspeed/ground speed	X	X	
Modified (acceleration-augmented) integrated flight director	X	X	
Synthesized reference glide path		X	
Go-around advisory:			
Acceleration margin	X	X	
Microprocessor display	X	X	
Modified go-around guidance for maximum performance	X	X	X
Angle-of-attack display	X	X	
Manual control for maximum performance			X
Wind information in real time	X	X	

and the simulated situations under which they were tested. Detailed descriptions of the aids appear in a subsequent section of this report. In earlier tests, approaches and landings had been simulated at a sea-level runway; approaches in this test used a runway at an elevation of 5,300 feet, 95°F (9000 feet density altitude) to simulate worst-case conditions. Takeoffs were made from sea level. Another departure from previous exercises was that subject pilots were asked to execute a go-around when advised and according to the guidance provided; the performance of the system was tested directly.

Test planning and engineering development work started in April 1978. On 10 May, a test plan was submitted to the FAA. A request for proposal on simulation support was sent to Douglas, who responded with their proposal 78D-217; a subcontract was negotiated and Douglas started work on 29 June. Coordination meetings were held in August. The FAA let a separate contract to Kollsman Instrument Company for the provision of analog instruments. Specifications for sensors, instrument drive signals, and go-around signals were sent to Douglas in September. On 5 October, Collins delivered specifications for the modified flight director steering and integrated thrust-command signals. Bunker Ramo prepared briefing materials and evaluation questionnaires for the subject pilots. Simulator checkouts started at Douglas on 6 November. The microprocessor display was installed in the simulator on the 9th, and Kollsman instrument was installed on the 13th. The weeks of 13-17 November and 27 November-1 December were used for checking out the instruments, refining the control algorithms, and making final adjustments of control parameters. The FAA added briefing material, and BR recruited the subject pilots. Runs with subject pilots in the precision approach test were made on 11-12 December, 15-17 January, and 26 January; the 10 pilots made 200 familiarization and 150 test runs. Simulator and instrument checkout trials were held on 4 January. The non-precision approach test was run in 8-12 January, the 10 subject pilots making 221 familiarization runs and 150 for test. The DC-10 simulator in takeoff configuration was checked out, takeoff control algorithms were installed and adjusted, and informal takeoff trials were conducted by the three project pilots on 22-25 January; this included 14 runs for familiarization and 60 for test.

Presentations of the results of the tests and demonstration runs on the MBDFS were held for industry and government representatives in March at Long Beach, California.

The FAA Wind Shear Program is under the supervision of Mr. H. Guice Tinsley. Lt. Col. Larry Wood, U.S. Air Force and FAA, is the manager for airborne systems, took part in the pilot briefings, and was one of the project pilots. Mr. W. Joe Cox was the FAA technical officer for this effort.

The AWLS project supervisor is Mr. Dean F. Babcock (SRI). At SRI, Dr. Wade H. Foy is the project leader; Mr. Walter B. Gartner designed the test and was responsible for the evaluation of the results. Mr. Gordon

K. Zunker (consultant) contributed to the test plan and other basic task documents. Dr. A. C. McTee led the BR effort and was test director. Capt. William O. Nice and Col. Don M. Condra of BR were project pilots and test observers, acting the role of first officer for the subject pilot runs. At Collins, the work on the modified flight director algorithms was supervised by Mr. Jim L. Foster; Mr. Dave Tiedman was project engineer and supported the tests at Douglas. The Douglas team was managed by Mr. John D. McDonnell, while Mr. Ernest Admiral was responsible for simulator hardware and test integration and Mr. Paul Jernigan was responsible for simulator software; many other Douglas personnel supported the simulation activities or did duty as test pilots for checkout and trial runs. The successful completion of the tests was dependent on the active and cooperative spirit of all these members of the task team.

The pilots who acted as subjects for the test runs are listed in Table 3. They include 13 from the airlines, 3 from air transport manufacturers, 2 from the Air Force, and 2 from FAA. All contributed their time and expertise without remuneration from the project; their professional competence and dedication had much to do with the success of the simulation effort.

C. Organization of Report

The report is organized to describe the three tests and to give their results in detail. The section that follows gives the simulator configuration and the wind conditions programmed in the simulation computer. The various aiding techniques, control algorithms, and information displays are discussed in Section III. Combinations of these made up the wind-shear aiding systems tested. Section IV through VI describe the separate tests: precision approach, non-precision approach, and takeoff. The conclusions drawn from the test results and our recommendations to the FAA are presented in Section VII. Various technical details, including a description of the microprocessor display, can be found in the appendices.

Table 3

SUBJECT PILOTS

Precision Approach Test	
Jack L. Brown	United Air Lines
Jerry Frederickson	Northwest Airlines
J. R. Gannett	Boeing Flight Test
R. F. Hanna	American Airlines
Thomas Imrich	FAA, AFS-203
R. J. Levendoski	FAA, AFS-203
R. O. Nelsen	Continental Air Lines
R. E. "Dick" Norman	National Air Lines
B. M. Richards	Continental Air Lines
W. R. Sonneman	Trans World Airlines
Non-Precision Approach Test	
William A. Brown	Pan American Airlines
Lt. Col. William A. Browning	U.S. Air Force, 4950 Test Wing
D. E. Cloud	American Airlines
Ralph C. Cokeley	Lockheed Aircraft Corporation
Maj. Paul C. Connors	U.S. Air Force, 4950 Test Wing
Don DeBolt	Northwest Airlines
H. Ray Lahr	Air Line Pilots Association
Sam S. Miller	United Air Lines
Ivan H. Shimon	American Airlines
W. David Wiebracht	Douglas Aircraft Company

II SIMULATION

A. DC-10 Simulator

The Douglas MBDFS, shown in Figure 1, consists of a modified DC-10 cockpit mounted on a six-degree-of-freedom moving base. A Redifon Visual system is used to represent the external visual scene. Programs for data acquisition and DC-10 equations of motion are mechanized on a Sigma-5 hybrid computer. The simulation was modified to include specified wind-shear and turbulence models. Cockpit instrument panels were reconfigured to include the experimental displays.

The modified DC-10 cockpit contains Captain, First Officer, and Instructor stations. The Instructor station, located aft of the Captain's station, was equipped for selection of test conditions, and control of mission start, reset, and position freeze. Subject pilots flew simulated approach or takeoff sequences from the Captain's station with the basic configuration shown in Figure 2. All flight controls, flight instruments, guidance systems, and aircraft subsystems necessary for the performance of this study were provided at the Captain and First Officer stations. Except for experimental displays, installed cockpit equipment conformed with standard DC-10 aircraft equipment.

The Sigma-5 provides program control of data collection and of simulated aerodynamic response, winds, and turbulence, with appropriate parameter values obtained from lookup tables. Wind profiles and turbulence conditions represented in the simulation were noted during each simulator run, and were shown together with aircraft variables of interest on a multichannel strip-chart recorder; at the end of each run a "quick look" summary was provided by output on the computer line printer.

The external visual scene is generated by a Redifon rigid model system with a scale factor of 750 to 1. The visual scene is represented by a 620-line color television image, and is displayed by high-resolution

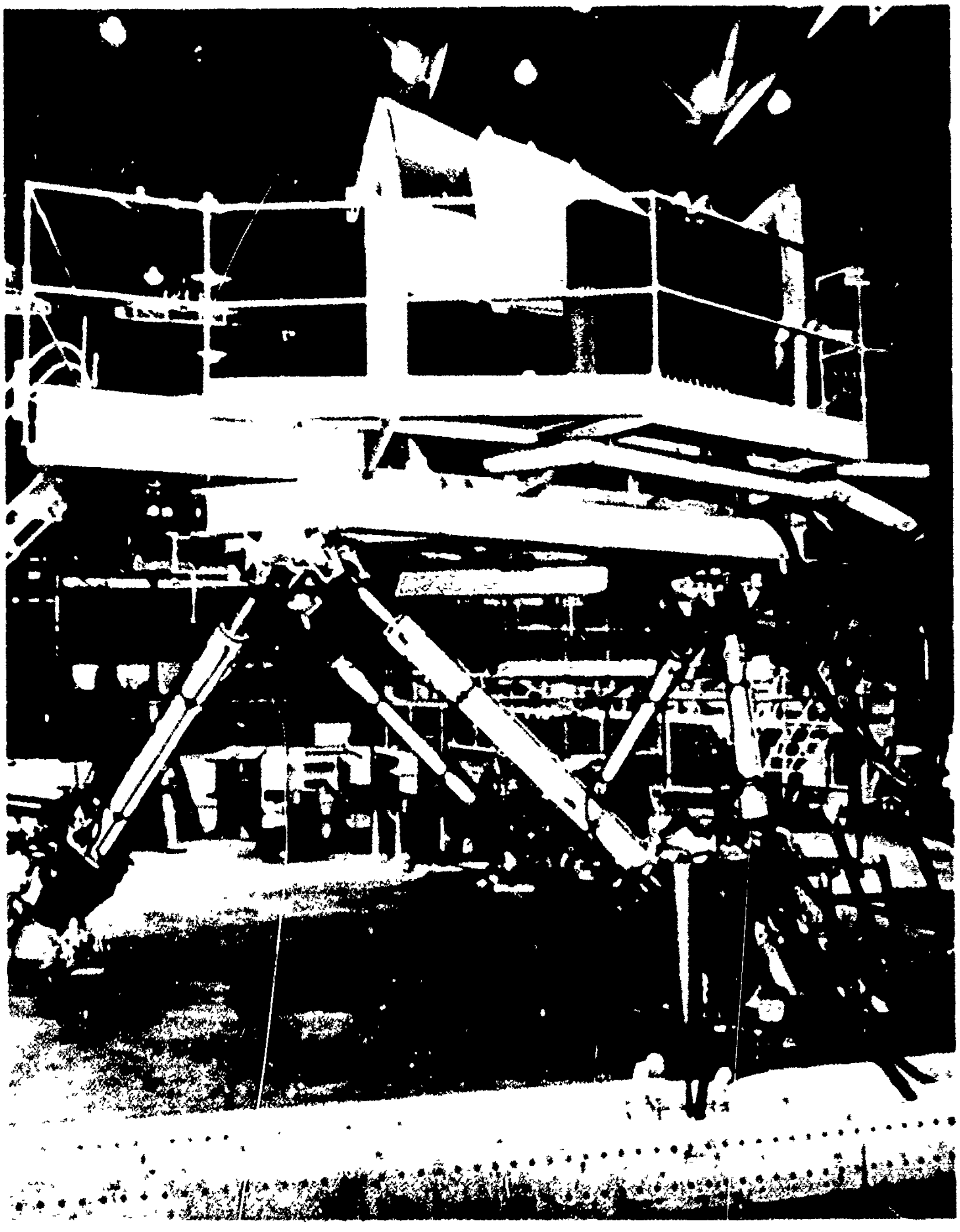


FIGURE 1 DOUGLAS MOVING-BASE DEVELOPMENT FLIGHT SIMULATOR

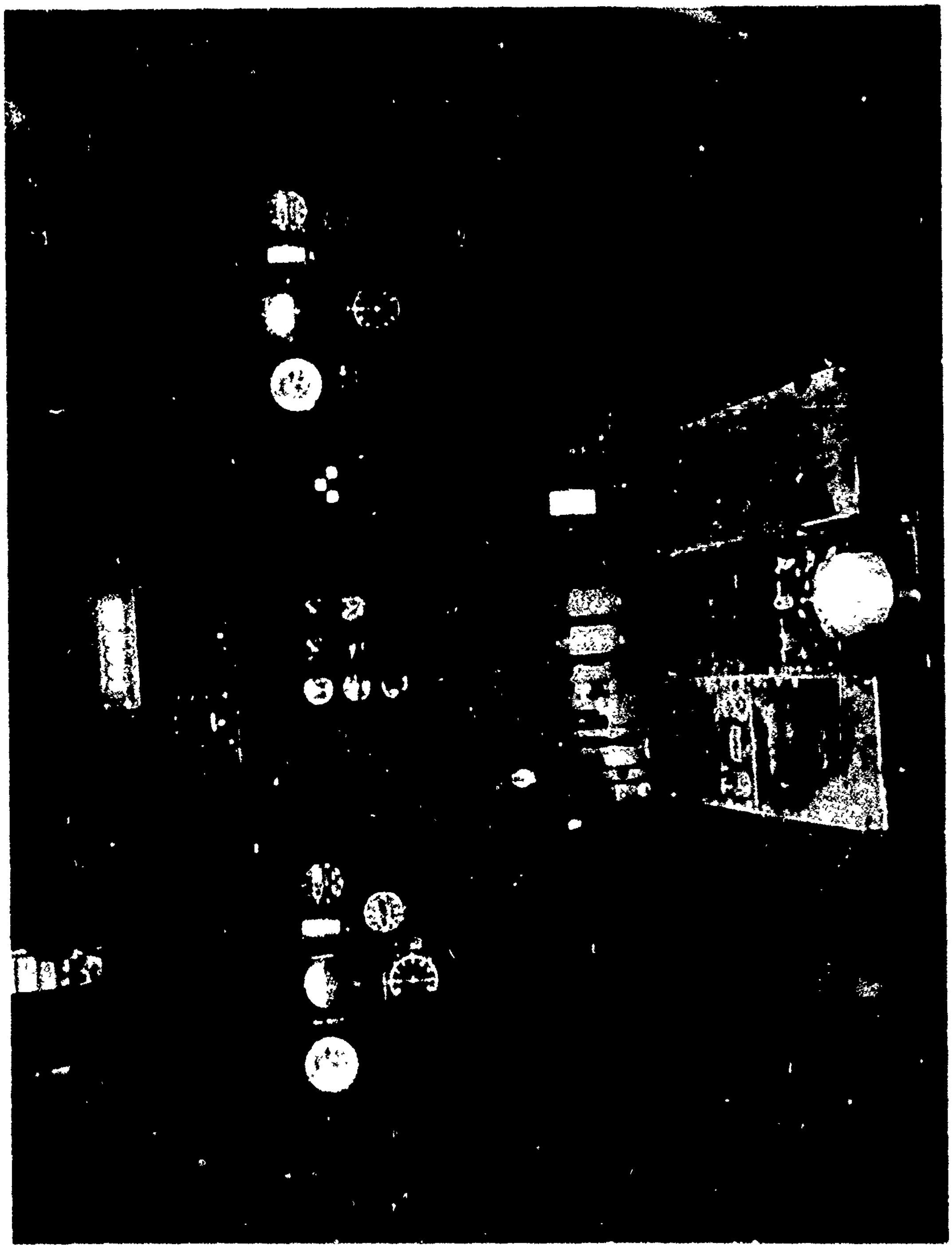


FIGURE 2 SIMULATED DC-10 COCKPIT

monitors viewed through a special Douglas Aircraft assymmetric lens. The Captain and First Officer stations are each equipped with a separate monitor and lens. The visual system has a maximum approach distance of 2.25 miles and an eye altitude range of 725 feet to 15 feet. Approach and strobe lighting are realistically simulated under variable ceiling and runway visual range (RVR) conditions.

The simulator has six degrees of freedom, provided by a six-jack (Franklin Institute) motion base. Motion is controlled from a ground control station located adjacent to the cockpit/platform. Motion capability is summarized in Table 4.

Table 4

SIMULATOR MOTION LIMITS

Axis	Excursion	Velocity		Acceleration	
		Payload 20,000 lb	Payload 3,600 lb	Payload 20,000 lb	Payload 3,000 lb
Heave	±42 in.	±39 in./s	±40.5 in./s	±1.65 g	±1.65 g
Sway	±67.5 in.	±67 in./s	±72.3 in./s	±1.43 g	±2.25 g
Surge	±65 in.	±71 in./s	±71.6 in./s	±1.50 g	±2.6 g
Roll	±30.7°	±35.6°/s	±36.2°/s	±7.8 rad/s^2	±7.8 rad/s^2
Pitch	±33.3°	±33.6°/s	±32.0°/s	±7.8 rad/s^2	±7.8 rad/s^2
Yaw	±38.7°	±36.3°/s	±40.3°/s	±7.9 rad/s^2	±7.8 rad/s^2

Equations of motion for the DC-10 series aircraft provided continuous flight simulation over the low-speed flight envelope. Table lookup functions were used for nonlinear aerodynamic data such as lift, drag, rolling, yawing, and pitching moments. Ground effects on aerodynamic coefficients were simulated over the entire flap range. Nonlinear lateral control spoilers were included. Control surfaces were simulated as either first- or second-order systems, with dead zones and position limits included for all surfaces.

B. Wind Profiles

Wind profiles selected for use in the simulator tests represent three broad classes of meteorological conditions commonly recognized as significant producers of low-level wind shear:

(1) Atmospheric boundary conditions

(2) Frontal systems

(3) Thunderstorms.

Wind data came from tower measurements, accident reconstructions, and meteorological math models; the data for each condition were converted to a three-dimensional wind field programmed as a function of altitude and longitudinal position. A number of different wind profiles were produced from each wind field by varying the runway position relative to each wind field and, where applicable, by varying the parameters of the wind model. Potentially hazardous wind profiles were identified and sorted into three levels of severity by observing the responses of a fast-time computer model of the DC-10 piloted by an idealized controller algorithm. Ten wind models were selected for the approach and landing tests; these were the same winds as those used in the DC-10 advanced tests of September-October 1977. An additional five models were chosen for the takeoff runs in this test. Care was taken to maintain realism. Some wind profiles for approach and landing, for example, were thunderstorm models constructed during the investigations of actual accidents. A useful and challenging profile for takeoff was constructed by taking a thunderstorm model and translating the storm center horizontally with respect to the simulated runway until the winds encountered presented hazardous conditions.

The development of the models and the process by which they were classified as to severity are discussed in another report.[4] For completeness, the wind profiles and turbulence models are described in Appendix A. A significant change from the 1977 tests was that the turbulence intensities were reduced to half, for these validation tests. The effect was to give a realistic amount of turbulence without having it override the wind shear.

III DESCRIPTION OF AIDS AND DISPLAYS

The simulated DC-10 airplane was controlled manually by the pilot with reference to the flight director and other instruments, or to the visual scene; the throttles were set manually. Cockpit procedures were similar to those of normal airline operations, with the observer pilot (playing the first officer role) giving the usual altitude, speed, and sink-rate callouts. On approach, for example, the pilot "flew" on instruments until visual breakout and completed the landing by visual reference. If a "go-around" (or "missed-approach") was made, he activated the take-off/go-around (TOGA) mode of the flight-director system, advanced the throttles, and controlled the aircraft via the flight-director commands; the first officer handled flaps and landing gear. The standard or "baseline" system and procedures for flight management, both for approach and landing and for takeoff, were a duplication of those recommended by Douglas for conventional airline passenger operations. The baseline system included only the conventional DC-10 instruments--flight-director drive signals and displays. Throttle management was normal, intended to maintain the preselected indicated airspeed. The instruments for all techniques were driven from the simulator computer by the sensor models described in Appendix B.

The "systems" tested for aiding the pilot in coping with low-level wind shear included various additions or changes to the conventional DC-10 system. These additional aids are described in the following paragraphs.

A. Airspeed/Ground Speed Technique

Previous studies[1-3] showed that a useful aid in wind shear is to replace the conventional airspeed-error thrust management with a technique designed to maintain both airspeed and ground speed (GNS). Given the pilot's selected approach speed, V_{app}, in terms of indicated airspeed, we calculate a reference ground speed, GNS_{ref}, as follows:

$$GNS_{ref} = TV_{app} - WX_{gnd}$$

where

TV_{app} = V_{app} converted to true airspeed (knots)

WX_{gnd} = Wind component at ground, longitudinal, with headwind positive (knots).

The aiding technique is to adjust the throttles so that the indicated airspeed is at or above V_{app} <u>and</u> the ground speed is at or above GNS_{ref}. The effect, when flying with a strong headwind that will disappear at the ground, is to require an airspeed higher than normal (V_{app}) as protection against the shear-out of the head wind.

In one display tested, this technique was implemented on the usual round-dial airspeed indicator by driving a second needle, the V_{mo} pointer, to read GNS. Colored "bugs" were positioned on the edge to indicate V_{app} and GNS_{ref}. This implementation with a dual-needle indicator was the same as that used in previous simulation tests.[2]

This airspeed/groundspeed technique was also incorporated in a speed command on the flight director; see Section II.F.

B. <u>Acceleration Margin</u>

An analog quantity designed to indicate when the airplane is getting into a hazardous situation with respect to longitudinal wind shear is its acceleration margin, ΔA, computed as:

$$\Delta A = A_{cap} - [-WD] \frac{\dot{H}}{H}$$

$$WD = (TAS-GNS) - WX_{gnd}$$

where

A_{cap} = Acceleration capability of the airplane in level flight in approach configuration (knots/s).

WX_{gnd} = Wind component at ground along runway, with headed positive (knots)

TAS = True airspeed of airplane (knots)

GNS = Ground speed of airplane (knots)

WD = Wind difference (knots)--difference between along-track wind at present position and on the runway

H = Altitude of airplane CG above ground, positive up (feet)

$\dot{H}$ = Rate of change of altitude with time, positive up (feet/s).

In this, A_{cap} is a constant for the approach and will depend on the selected approach speed, the flap setting, the maximum engine thrust available, the drag, the aircraft weight, and the air density; for instance, values for the DC-10 at 350 klb, 50° flaps, nominal approach speed, gear down, level flight, are:

Sea level, standard day	1.67 kt/s
9000 feet, standard day	1.00 kt/s

The term TAS - GNS is approximately the longitudinal wind velocity at the airplane, headwind positive, so WD is the wind difference or estimated wind shear, the change in wind between airplane present position and the ground; a decreasing headwind is a positive difference. The magnitude of $H/\dot{H}$ is the expected time in seconds to reach the ground, and $\dot{H}$ will be negative for descent. Thus, the term $[-WD]\dot{H}/H$ is the expected <u>acceleration demand</u> due to longitudinal wind shear, with a decreasing headwind for a descending aircraft giving a positive demand. If the demand equals or exceeds A_{cap}, ΔA becomes zero or negative and the situation is potentially hazardous.

Previous tests[3] showed that the condition $\Delta A \leq 0$, if used as a criterion for advising a go-around, produced too many nuisance alarms. Analysis of the runs and preliminary trials in the DC-10 simulator indicated that it would be useful to augment the algorithm. Let us compute the difference, DA, between the wind change and the airspeed pad by:

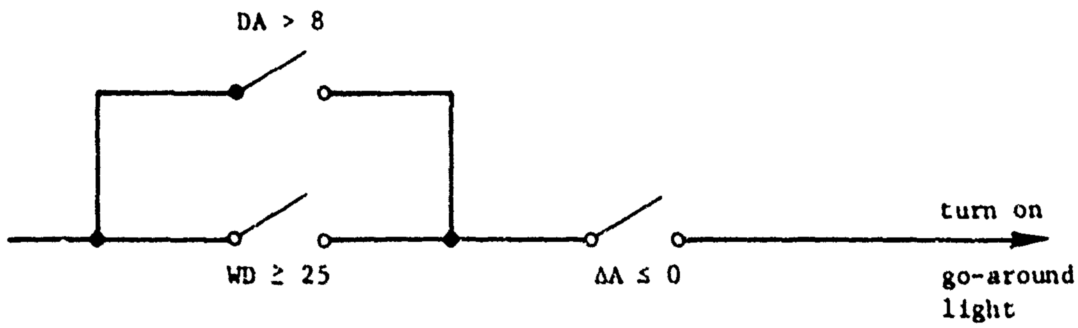
$$DA = WD - (IAS - V_{app})$$

where

IAS = Indicated airspeed (knots)

V_{app} = Selected approach speed (knots).

Then we implement a go-around advisory, closing the "switches" when the indicated condition is "true," as follows:



Thus, a go-around was advised, and a yellow "go-around ΔA" light on the instrument panel was lit, if $\Delta A \le 0$ AND if [$WD \ge 25$ knots OR $DA > 8$ knots]. The effect is to inhibit the go-around advisory if either the wind difference (decreasing head wind) is less than 25 knots or the wind difference is no more than 8 knots greater than the airspeed pad. The particular values 8 and 25 knots were chosen empirically.

C. Moving-Tape Display

The simulated airplane can be "flown" by reference to the flight director steering and Fast/Slow commands alone if there are no failures. However, the pilot requires backup or ancillary information that supplements and supports the flight director. This backup information is most useful if it is displayed in a way that permits easy assessments of the trends in time of the quantities. We expected that such a display that included acceleration margin and angle of attack, in addition to the standard information (airspeed, altitude, vertical rate), would be effective if the information could be displayed in the comparatively small area of the instrument panel normally scanned by the pilot. Therefore the FAA technical monitors designed the moving-tape display shown in Figure 3. The 3-tape instruments, Kollsman model AVK-16/A 24G10, were borrowed from the USAF Flight Dynamics Laboratory and were modified by Kollsman Instrument Company on a separate FAA contract. The right and middle tapes show indicated airspeed and ground speed. The left tape reads out the negative of the acceleration demand (see p. 17) scaled by 2 (i.e., -2 on the tape corresponds to +1 knot/s of acceleration demand). The solid-color strip (red) on the negative region ends at the

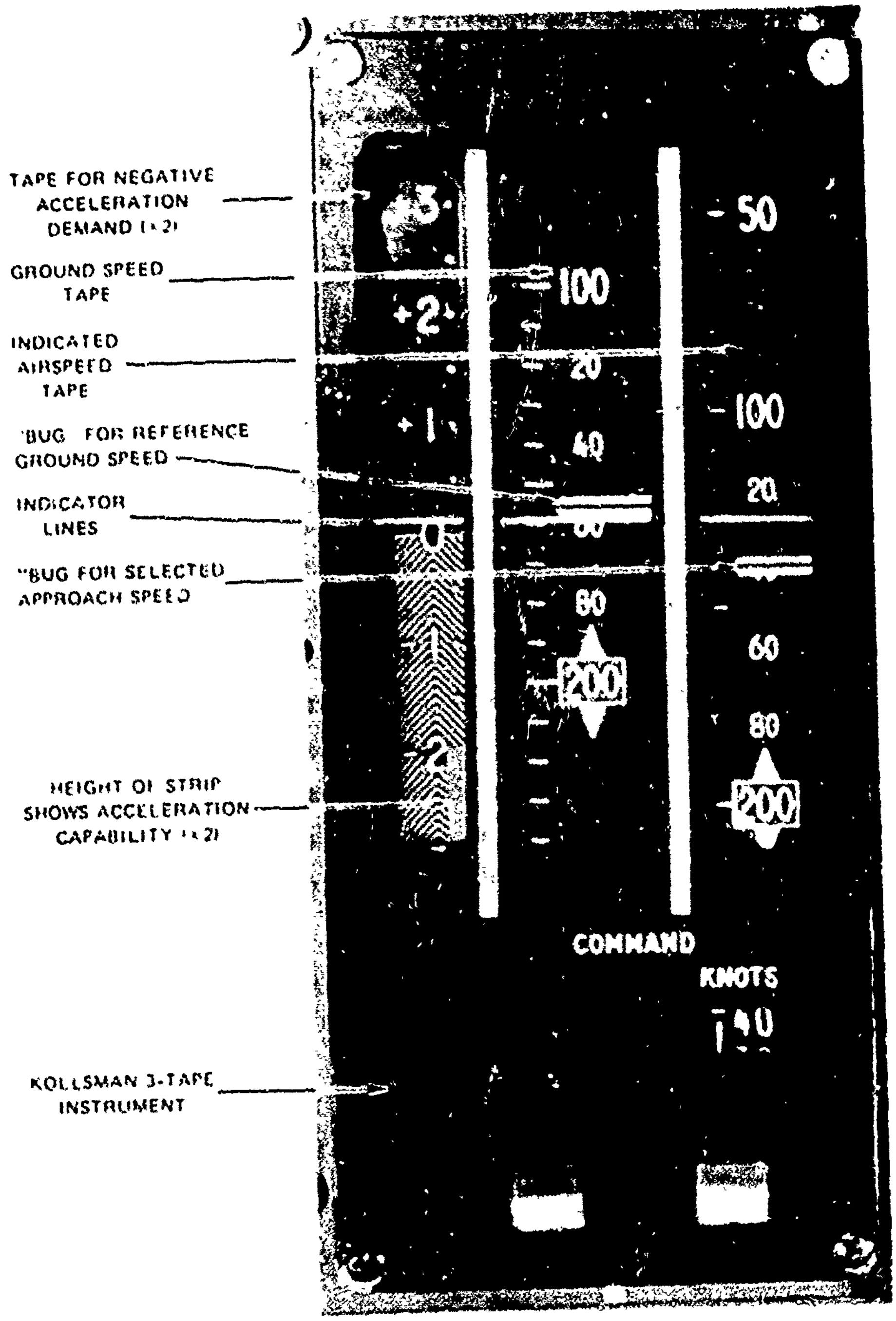


FIGURE 3 MOVING-TAPE DISPLAY

corresponding value of aircraft acceleration capability; thus, if the tape shows the indicator line in the solid strip, the acceleration demand is greater than the capability, ΔA is negative, and a go-around may be advisable. A positive reading (above zero) on this tape indicates a performance-increasing condition (potential airspeed gain) ahead of the aircraft. A negative reading (below zero) indicates that a performance-decreasing condition (potential airspeed loss) will be encountered. As the figure shows, this instrument, when used, was mounted to the left of the flight director in the position usually occupied by the normal airspeed indicator. The moving-tape displays were installed on both pilot's and copilot's instrument panels.

D. Longitudinal Displacement and Synthetic Glide Path

A basic assumption of the aiding concepts was that a measurement of ground speed (GNS) would be available in the airplane simulated. The model for this measurement is given in Appendix B; note that it included an additive random component of 4 krots rms. From this assumption it is an easy step to assume also that a measurement of initial position can be made. Examples of possible sources are a position fix from the airplane's standard navigation method, a distance-measuring-equipment (DME) reading, or the point of crossing the center of the outer marker beam on approach. With the initial position and GNS, we may compute horizontal displacement along the runway centerline by integrating

$$X_m = X_o + \int_o^t (GNS)dt$$

where

$X_m(t)$ = Measured longitudinal displacement of airplane, positive in direction of approach

X_o = Initial value of longitudinal displacement.

An error in initialization will appear as a constant bias error in X_m. We took a value of ± 600 feet, corresponding to a single-reading DME bias, as the initialization error. On each simulator run the particular value of the X bias error was dependent on the wind profile, being selected to cause the most difficulty; for instance, an error of +600 feet was applied to runs on a wind profile where a headwind loss was expected.

The measurement of X with the standard measurement of airplane altitude above ground, from a radio altimeter, for instance, may be combined to synthesize a reference glide path when an ILS glide slope beam is not available--as on non-precision approach. Assuming that X = 0 at the glide path intercept point on the runway, we computed:

$$H_{gp} = -X_m \tan(GSA)$$

where

H_{gp} = Height above ground, positive up (feet), of the glide path at longitudinal displacement X

GSA = Glide path angle (degrees) above horizontal; nominally 3°.

The altitude error of the airplane then was $H - H_{gp}$, which gave vertical deviation from the synthesized glide path and was used for flight director pitch commands Note that H_{gp} had a random error component due to the error applied to the GNS measurement; the effect of the integration and the small value of tan(GSA) was to attenuate this component so much that it was practically negligible. It was necessary to add a random noise component to the measurement of aircraft altitude, H, as shown in Appendix B, to get a "realistic" synthetic glide path. There was no intention or attempt to use this synthetic glide path below nonprecision minimums.

E. Modified Flight Director

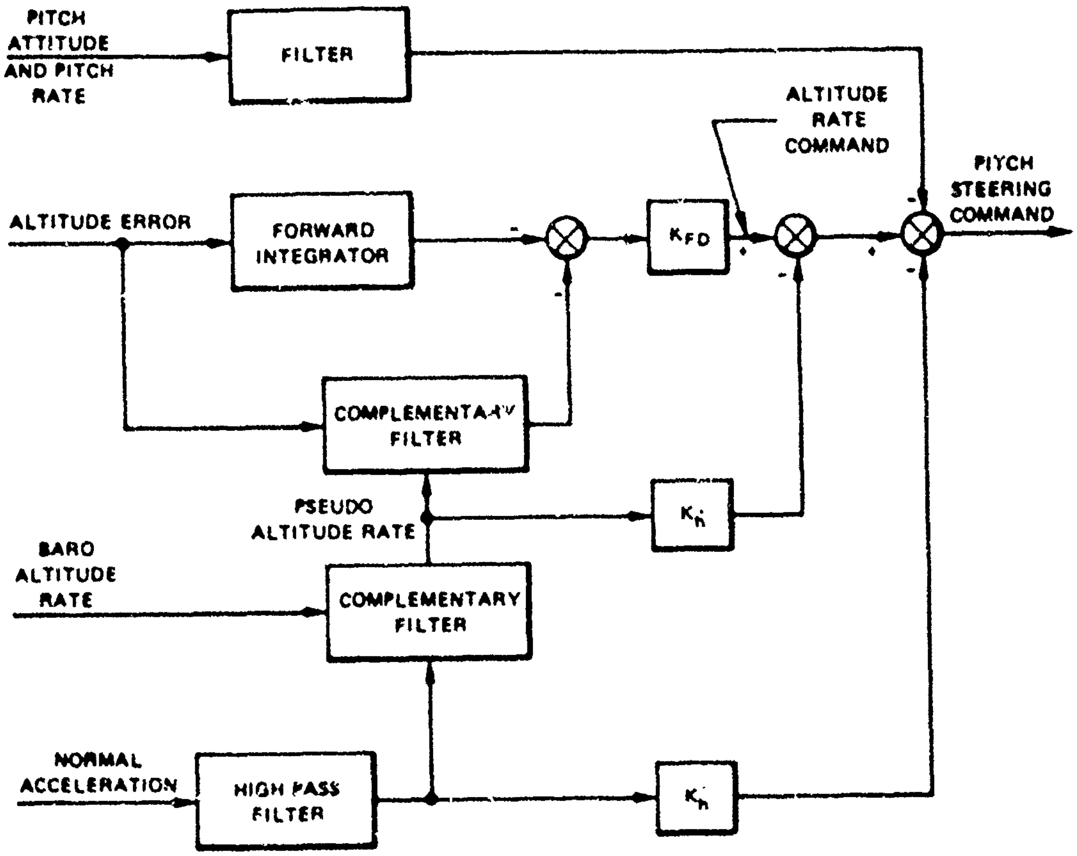
Under Task 5 of this AWLS contract Collins developed improved flight director control laws that incorporate acceleration augmentation to aid in coping with wind shear on approach and landing. In comparison with the standard or "baseline" flight director commands, these modified steering control laws exhibit quickened responses to changing wind and other transients. The modified flight director also had a modified speed command, driving the Fast/Slow "bug," that used acceleration augmentation and wind-shear compensation to improve speed control. The modified flight director (MFD) laws for this DC-10 simulation test had no major changes from those of the previous tests; previous reports[2,3] describe the algorithms and compare them to the baseline DC-10 flight director laws. To illustrate the techniques, simplified block diagrams of the MFD longitudinal and lateral controls are given in Figures 4a. and b., and a similar diagram of the MFD speed control is given in Figure 5.

When used on a non-precision approach, the flight director pitch steering command requires a substitute for glide slope deviation. Note that the MFD longitudinal control, Figure 4, has altitude error as a basic input. On precision approach this signal was obtained from glide slope deviation and altitude. On non-precision approach, the altitude error signal was computed by using the synthetic glide path described above. Figure 6 shows this algorithm.

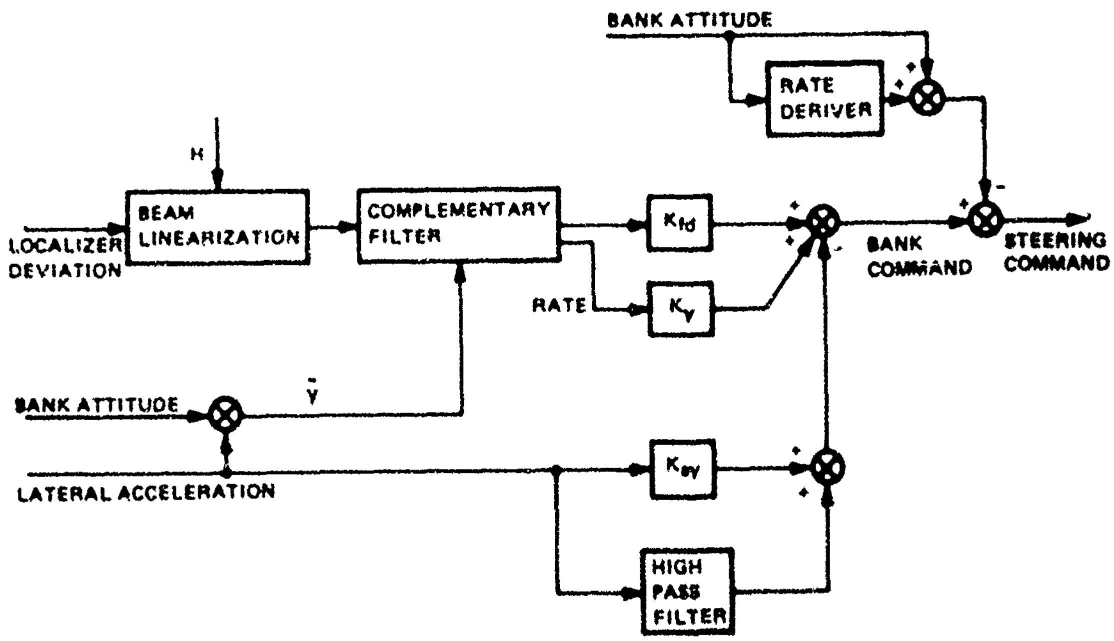
With the MFD the pilot's task was to steer the simulated airplane so as to follow the flight director steering commands as closely as possible. Thus, this part of the experimental task was the same in concept as conventional approach management by flight director reference. When the MFD was used, both the pilot's and the copilot's flight directors were driven by the MFD signals.

F. Thrust Command

For approach and landing the pilot's speed control task was aided by supplying a speed error indication on the Fast/Slow scale of the flight director. The pilot moved the throttles to keep the F/S indicator showing



a. PITCH STEERING



b. LATERAL CONTROL LAW

FIGURE 4 MODIFIED FLIGHT DIRECTOR

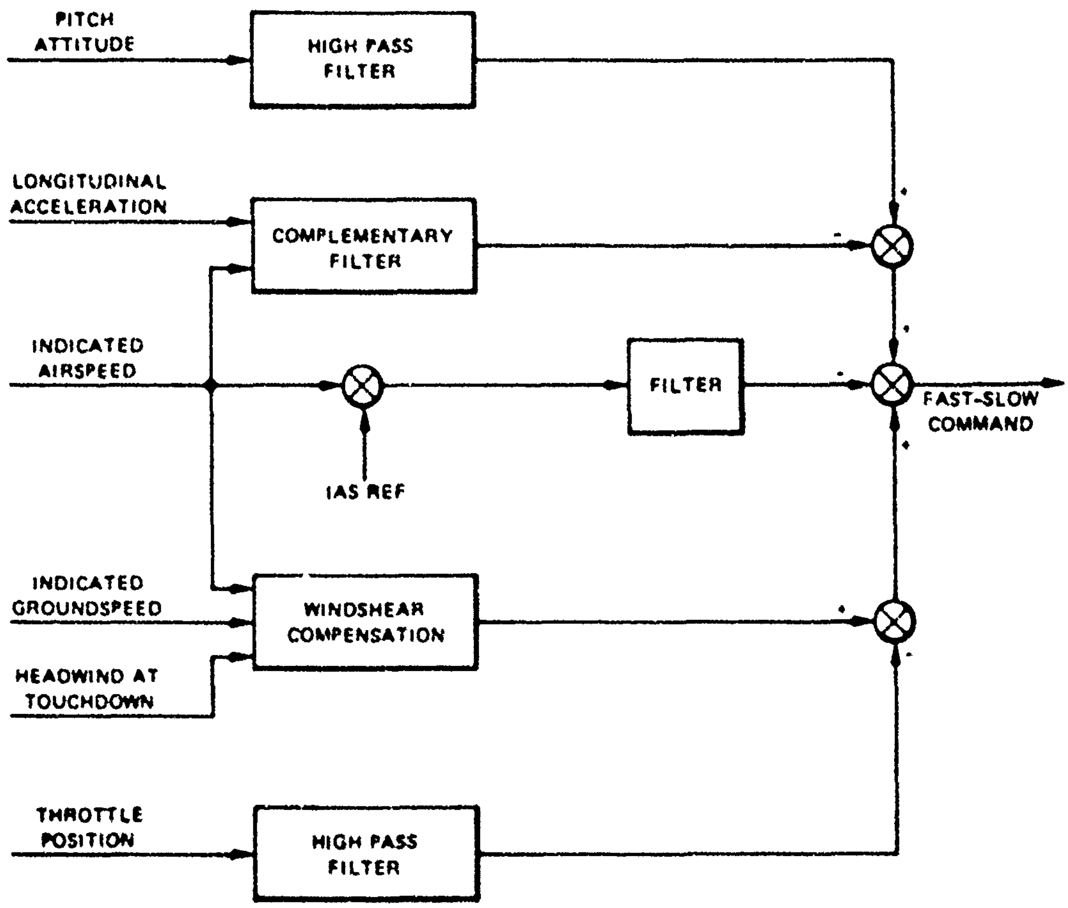
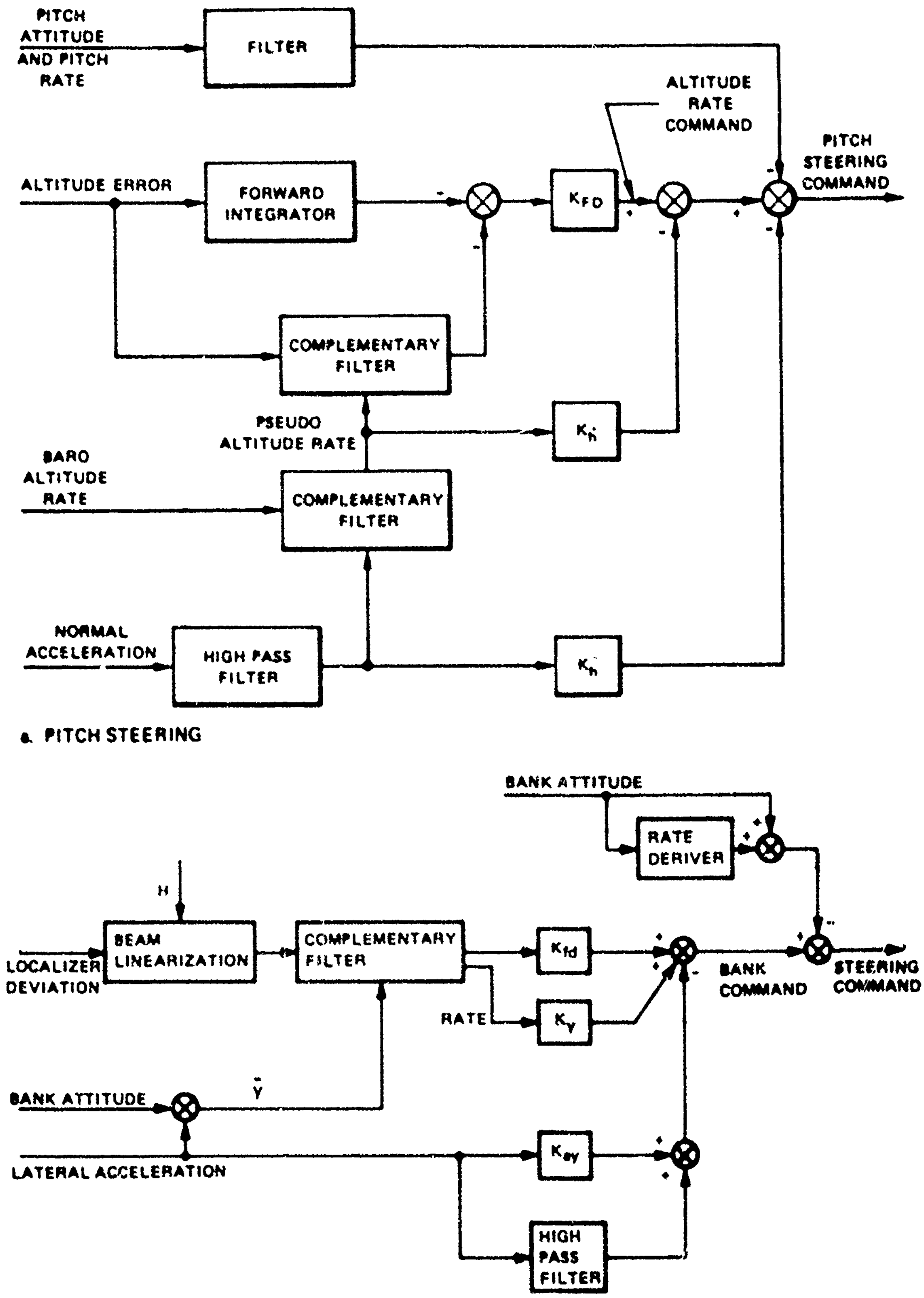


FIGURE 5 MODIFIED FLIGHT DIRECTOR — SPEED CONTROL



a. PITCH STEERING

b. LATERAL CONTROL LAW

FIGURE 4 MODIFIED FLIGHT DIRECTOR

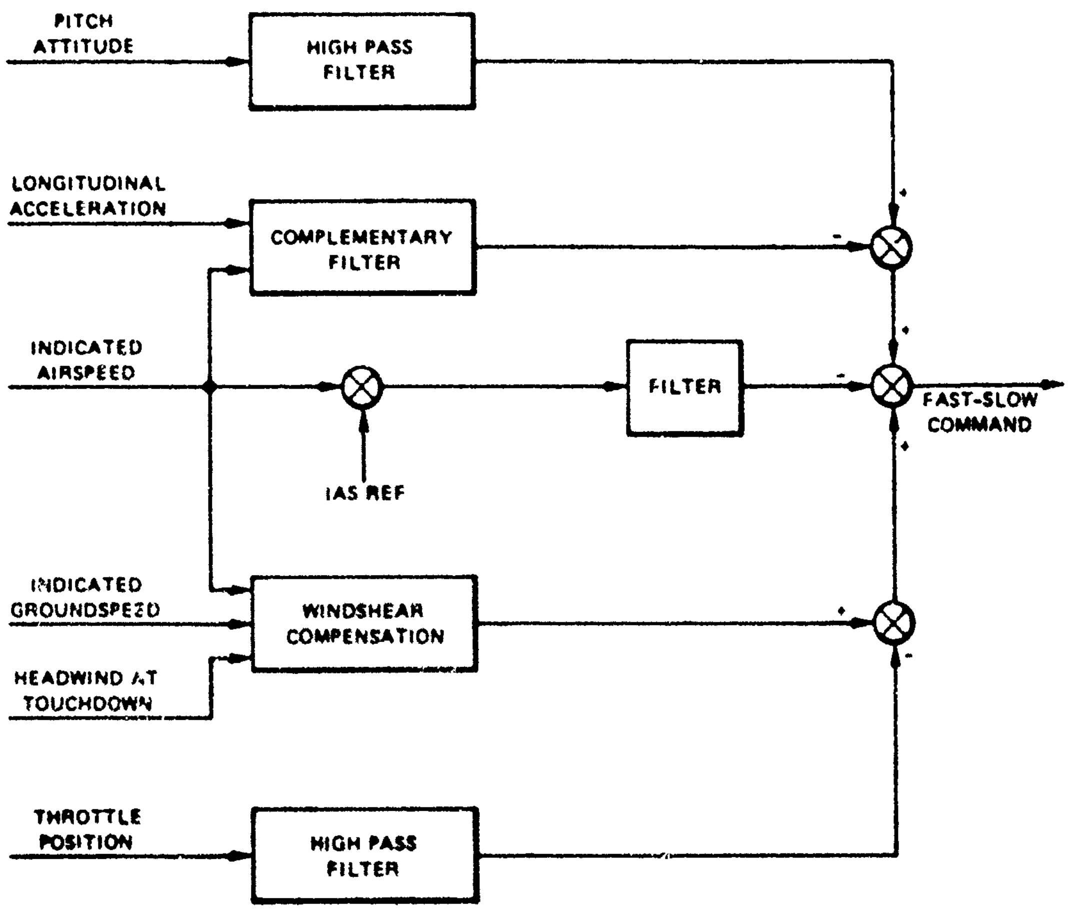


FIGURE 5 MODIFIED FLIGHT DIRECTOR — SPEED CONTROL

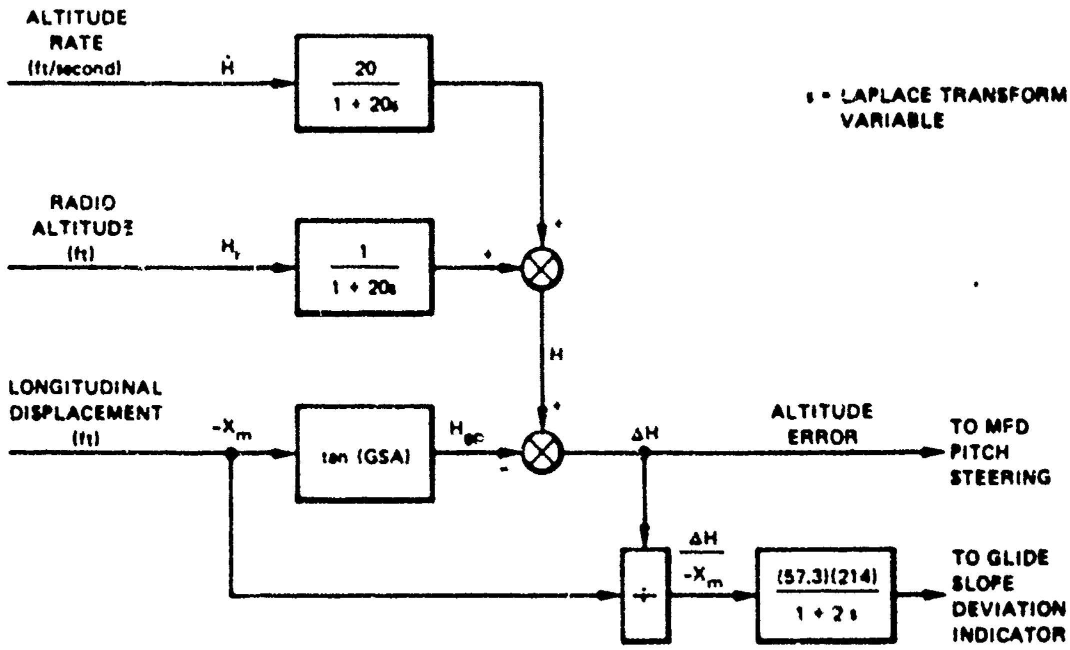


FIGURE 6 ALTITUDE ERROR FROM SYNTHETIC GLIDE PATH

zero error, in the conventional way. The dynamic effects of the simulated wind shears produced speed errors greater than 10 knots, however, so the conventional ±10-knot scale was changed to read ±20 knots.

Three speed-command algorithms were implemented in the simulation computer software. The "baseline" DC-10 F/S signal was derived primarily from airspeed error; it was designed to give smooth, stable operation. The Collins MFD algorithm was described above (Figure 5). The third F/S drive signal was the same one used in previous tests,[3] based on both ground speed error and airspeed error. The algorithm for computing that signal is:

$$F/S = \text{Minimum of } (\Delta AS, \Delta GNS)$$

$$\Delta AS = IAS - V_{app}$$

$$\Delta GNS = GNS - GNS_{ref}$$

where

F/S = Fast/Slow indicator reading (knots, limited to ±20)

IAS = Indicated airspeed (knots)

V_{app} = Selected approach speed (knots).

This "minimum airspeed-error/ground-speed-error" algorithm gives an F/S signal that duplicates the pilot's speed management technique described in Section III-A. When used, the pilot's and copilot's F/S indicators were driven.

G. Modified Go-Around Guidance

Situations will occur on approach and landing, especially with wind shear of high severity, for which the appropriate action is to abort the approach and make a "go-around." In the simulated airplane the pilot initiated the maneuver by pressing the TOGA button and saying "go-around;" he advanced the throttles to give full (102%) engine rpm and steered on the flight director commands, while the copilot activated the lever to raise the landing gear and moved the flap lever to 22°. The standard or "baseline" DC-10 go-around steering and F/S signals for the flight director are derived from heading, angle of attack, indicated airspeed, and longitudinal acceleration. They provide a smooth pitch-up maneuver.

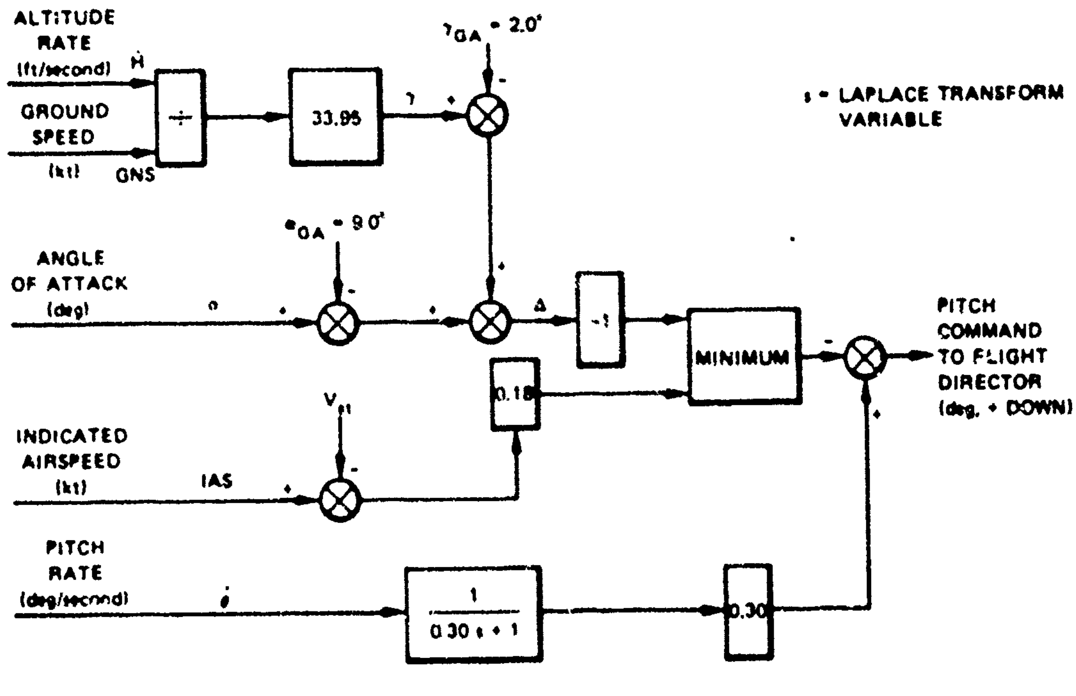
An alternative method was designed in an attempt to minimize the loss of altitude during the go-around. This modified go-around guidance, developed by Mr. David W. Ellis of SRI, was intended to provide a pitch steering control law for use in wind shear. The control law was designed specifically for the simulator validation tests, and would require additions and modifications if used in a production aircraft.

The rationale of the design is as follows:

- The dominating requirement during go-around is terrain avoidance and obstacle clearance. After the initial pitch-up maneuver, it is assumed that flying a nominal positive flight path angle will result in a safe go-around.
- The pitch attitude required to maintain a flight path is dependent on the prevailing wind. The steering control law should contain compensation for this effect.

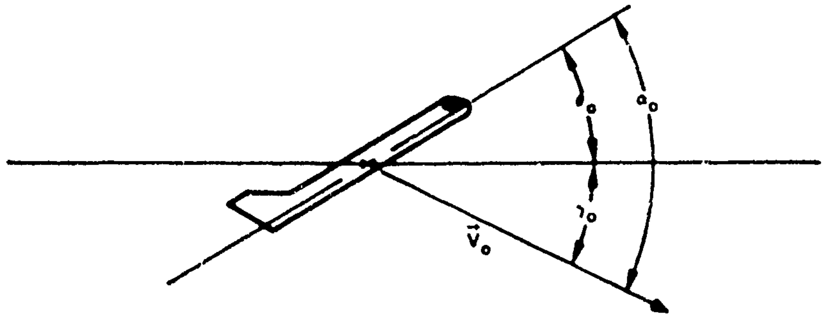
- If there is severe wind shear or some other condition such that the aircraft cannot maintain the nominal flight path angle, the aircraft will be flown at or above a minimum airspeed at a commensurate maximum pitch attitude.

The design is described schematically in Figure 7. Vertical-speed $\dot{H}$ and ground-speed GNS inputs are used to compute flight-path-angle γ. Flight-path-angle and angle-of-attack α then go into the computation of the pitch steering signal Δ. This computation may be explained with the aid of the vector diagrams in Figure 8. In Figure 8(a) the aircraft is

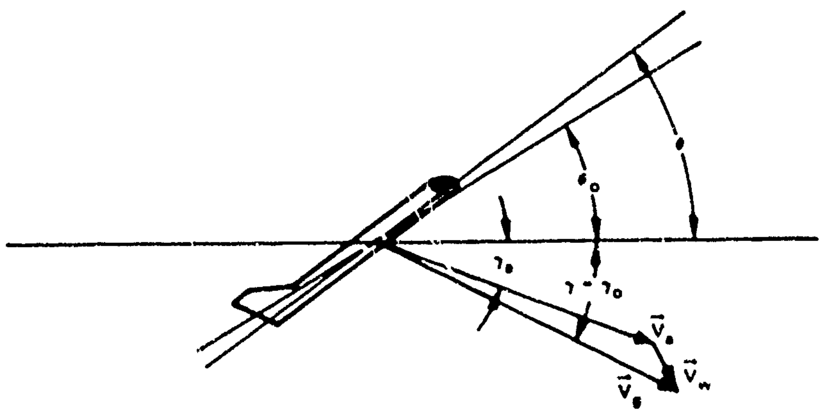


V_{st} = STALL AIRSPEED, DEPENDENT ON FLAP POSITION

FIGURE 7 MODIFIED GO-AROUND PITCH STEERING



(a) AIRCRAFT IN STEADY FLIGHT WITH NO WIND



(b) AIRCRAFT IN STEADY FLIGHT WITH WIND

FIGURE 8 EFFECT OF WIND ON AIRCRAFT FLYING AT A GIVEN γ

shown at a given flight-path-angle γ_o with no wind. In Figure 8(b) the aircraft is at the same flight-path-angle γ_o with the exception that a steady wind component V_w has been introduced. To compensate for the wind, the aircraft has been pitched up by approximately $\gamma_a - \gamma$. If winds were ignored (treated as a disturbance) in the control law, one could write:

$$\Delta = \theta - \theta_o$$

where θ is the pitch angle. To compensate for the wind, we want:

$$\Delta = \theta - [\theta_o + (\gamma_a - \gamma)]$$

which, with the substitutions $\gamma_a = \theta - \alpha$ and $\theta_o = \gamma_o + \alpha_o$, is equivalent to

$$\Delta = \theta - [\gamma_o - \alpha_o + (\theta - \alpha - \gamma)]$$

$$\Delta = (\gamma - \gamma_o) + (\alpha - \alpha_o).$$

This signal and the pitch rate term $\dot{\theta}$ for damping are the controlling terms as long as airspeed remains high. When airspeed drops to or below the stall value, the minimum function chooses the IAS-V_{st} input, which results in a pitch-down command to gain airspeed. The reference flight path angle, γ_{GA}, and angle of attack, α_{GA}, were chosen empirically to give a good DC-10 go-around maneuver.

With the modified go-around method the pilot advanced throttles to give full thrust immediately after pushing TOGA. He was then not using the F/S indicator on the flight director for the thrust control. Therefore, to provide additional information, the F/S signal was modified so that the F/S displayed an approximation to angle-of-attack error. The modified go-around signal drove both pilot's and copilot's flight director.

H. Run Evaluation (Microcomputer) Display

Previous wind-shear simulation tests[3] had exposed the need on approach and landing for an effective go-around advisory device that would be easy to read, reasonably inexpensive, and substantially free of nuisance alarms. We hypothesized that any go-around advisory should be accompanied by some explanation of the reason for the warning, and also that we could increase the usefulness of the device by providing indications of wind activity. Accordingly, SRI designed and developed a microcomputer-based alphanumeric unit termed the "run evaluation display" (RED). The window, in which

20 characters could be displayed, is shown in Figure 9. Two of these units were mounted on the simulator instrument panel, one on each side, just above the barometric altimeters.

Twelve analog quantities representing sensor measurements were available in the simulated airplane, as shown in Table 5, and were provided in the DC-10 simulator as inputs to the multiplexed analog-to-digital converter of the microprocessor. The binary TOGA-button contact was also provided, as were two simulator binary events needed to initialize the calculations. The microprocessor sampled the analog quantities once each second and computed air-mass flight path angle, longitudinal and vertical wind at the aircraft position, and estimated longitudinal wind shear. If the airplane was located before the runway threshold on approach it computed the estimated height loss if a go-around were executed, and the altitude of the obstruction clearance zone; if the simulated aircraft had crossed the runway threshold it computed the estimated distance to touchdown and to stop, assuming a wet runway. Depending on the results of the computations, the microprocessor put one of the following messages on the alphanumeric display, with the appropriate numerical figures inserted:

- <u>Surface Wind Message</u>

  `NR HW 32K FAR TW 47K`

  The wind along the runway is 32 knots headwind at the near end and is 47 knots tailwind at the far end.

- <u>Longitudinal Wind Shear Messages</u>

  `HW DEC SP LOSS 20K/H`

  `HW INC SP GAIN 15K/H`

  `TW DEC SP GAIN 29K/H`

  `TW INC SP LOSS 8K/H`

  The longitudinal wind at the airplane is a head (or tail) wind and will decrease (or increase) along the approach path; the estimated airspeed loss (or gain) is shown in knots per hundred feet of decrease in altitude. Shown if the wind shear is greater than 8 knots per 100 feet of altitude.

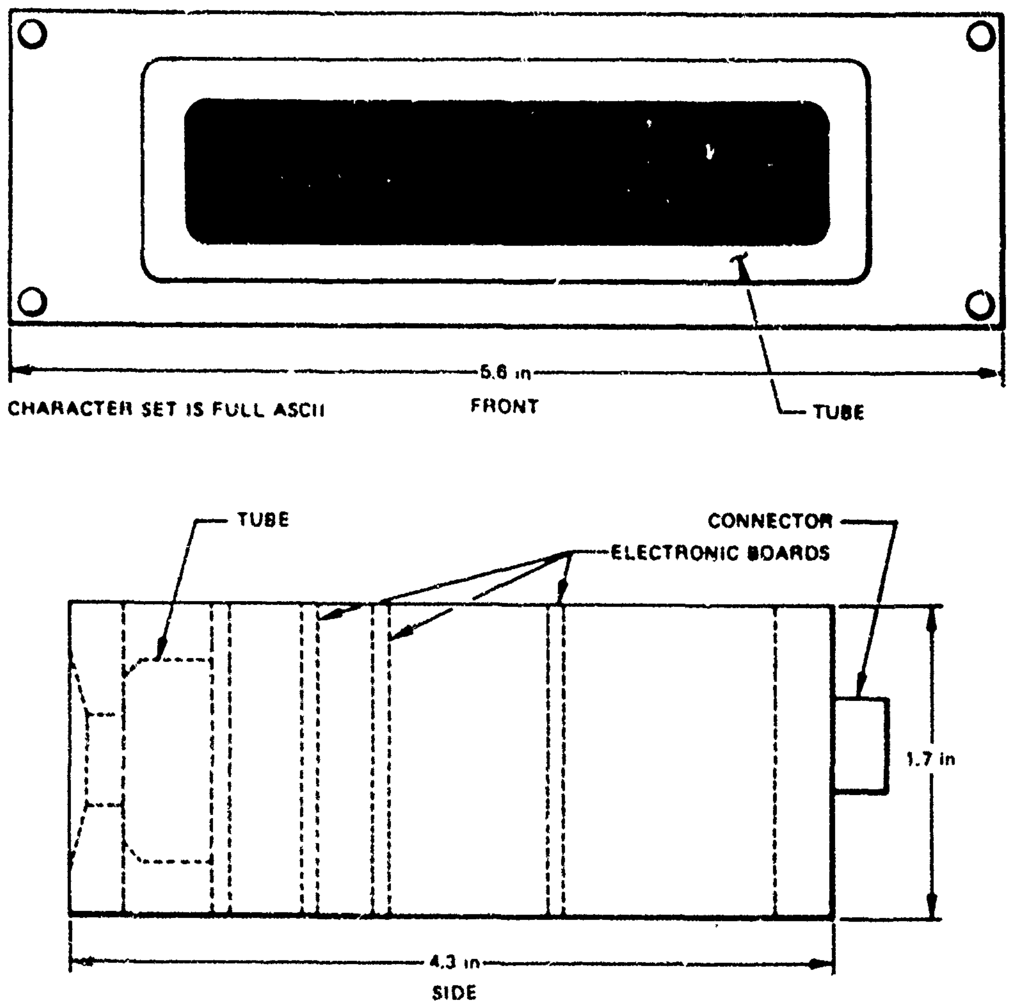


FIGURE 9 WINDOW FOR ALPHANUMERIC DISPLAY

Table 5

INPUTS TO MICROPROCESSOR FOR RUN EVALUATION DISPLAY

(a) Analog

Channel	Quantity	Symbol	Range	Sense
0	Pitch angle	θ	±16 deg	+ up
1	Angle of attack	α	±16 deg	+ up
2	True airspeed	TAS	0-256 kt	--
3	Ground speed	GNS	0-256 kt	--
4	Altitude above runway	H	0-2048	+ up
5	Vertical velocity	$\dot{H}$	±32 ft/s	+ up
6	Longitudinal wind at runway near end	VWX_{gnd}	±64 kt	+ tailwind
7	Longitudinal wind at runway far end	VWX_{far}	±64 kt	+ tailwind
8	Not used	--	--	--
9	Localizer deviation	ALOC	±2 deg	+ to right
10	Longitudinal displacement (fine)	X_f	±1024 ft	+ in direction of approach
11	Longitudinal displacement (coarse)	X_c	±32 kft	+ in direction of approach
12	Acceleration demand	A_{dem}	±8 kt/s	--
13	Indicated airspeed	IAS	0-256 kt	--

(b) Binary-Valued Event Markers

TOGA	Takeoff/Go-Around Button
RRST	Run reset
MNBN	Mission start

(c) Constants Required

Air density	ρ
Acceleration of gravity	g_o
Runway length	l_r
Nominal glide slope angle	GSA
Weight of airplane	W
Reference wing area	S
Drag coefficients	C_{DN}, C_{LREF}
Lift coefficients	C_{LO}, $C_{L\alpha}$ C_{LMAX}
Maximum available thrust	T_m

- Vertical Wind Messages

$\boxed{\text{VERT W UPDRAFT 17K}}$

$\boxed{\text{VERT W DOWNDRAFT 33K}}$

The aircraft is in a wind with a vertical component, updraft or downdraft, of the speed shown in knots. Shown if the vertical wind speed is greater than 5 knots.

- Airspeed Warning

$\boxed{\text{SPEED HIGH FOR FLAPS}}$

The indicated airspeed has exceeded the flap placard speed.

- Go-Around Advisory Messages, Aircraft Before Threshold

$\boxed{\text{GO ARND UNDERSHOOT}}$

The airplane position and velocity are such that there is danger of going too low and into the clearance zone.

$\boxed{\text{GO ARND ACCEL LACK}}$

The acceleration margin criterion has been met ($\Delta A \leq 0$).

$\boxed{\text{GO ARND OFF TO RIGHT}}$

$\boxed{\text{GO ARND OFF TO LEFT}}$

There is too much lateral deviation from the localizer.

$\boxed{\text{GO ARND SPEED LOW}}$

The airspeed has decreased to 10% above stalling speed or less.

- Go-Around Advisory Messages, Aircraft has Crossed Threshold

$\boxed{\text{GO ARND OVERSHOOT}}$

The position and velocity of the aircraft are such that there is danger of overrunning the far end of the runway.

$\boxed{\text{GO ARND DESCENT RATE}}$

The descent rate of the aircraft is too high for a safe landing.

The priorities with which the different messages were displayed were ordered for safety. That is, a go-around message overrode any other, the longitudinal wind shear or vertical wind messages (these were alternated if the situation had both conditions) alternated with the airspeed warning and overrode the surface wind, and the airspeed warning overrode the surface wind message. A technical description of the microprocessor display and details of the calculations are given in Appendix C.

When the display was installed in the DC-10 simulator and checked out, it was found to operate intermittently, presumably because of noise and/or crosstalk on the data and event lines from the simulation computer. The troubles were reduced by filtering the lines and by reprogramming the microprocessor to provide some protection against false signals, especially in the computation of go-around advisory conditions. All the problems were not eliminated, however. The microprocessor display operated as designed through some of the simulation run sessions, but there were enough faults to prevent a thorough evaluation.

I. Angle of Attack

We hypothesized that information on airplane angle of attack, α, would be useful in aiding the pilot to cope with updraft and downdraft wind, and would be particularly important for the go-around maneuver. Several candidates and displays were considered, but were rejected for various technical reasons such as lack of proper filtering. We decided that the most appropriate and effective way to use α information would be to incorporate it into the flight director steering and/or thrust commands. The Collins-designed MFD algorithms for approach did not need angle of attack; however, α terms were used in the modified go-around guidance with good effect.

IV PRECISION APPROACH STUDY

A. Situation Simulated

The simulated approach and landing scenario adopted for the precision approach study was a manually flown, flight director ILS approach. Simulated guidance signals included beam bends and beam noise to represent a Category I ILS. Cloud cover was simulated down to a breakout altitude of 150 feet above ground level (AGL), and simulated visual conditions after breakout represented a runway visual range (RVR) of 5000 feet. The terrain model/closed-circuit television system used to represent cloud cover during the approach and the external visual scene after breakout have been described in Section II. A 150-by-11,500-foot runway with standard markings and Category II approach and runway lighting was represented in the visual system.

Simulated approach sequences were initiated inside the final approach fix (Outer Marker) at an altitude of 1500 feet AGL with the landing checklist completed and the aircraft in the landing configuration (gear down and flaps extended). A landing gross weight of 350,000 lb was adopted and all approaches were flown with 50° flaps. At run initiation, the aircraft was positioned on glide slope and localizer and stabilized on a preselected target approach speed for the scheduled test conditions. The approach sequence was terminated after nose-wheel touchdown and a short rollout, after execution of a successful go-around maneuver, or after the occurrence of a crash.

Wind conditions were varied from run to run in accordance with the scheduled exposure to wind-shear conditions, as described below in Section IV-B.

Runway elevation was set at 5300 feet MSL on all runs and the ambient temperature on the ground was set at 95°F. These landing conditions correspond to an air density environment of 9000 feet MSL.

B. Systems Tested

1. The Primary Test System: MFD/ΔA

The primary test system consists of an integrated combination of the aiding concepts that have produced the most substantial improvement in coping with low-level wind shear in earlier simulator evaluation studies. The components of this system and the test instruments used in the present validation study are shown in Figure 10. A description of the drive signal computations and pilot technique associated with each component of this test system is given in Section III. In subsequent discussions of the evaluation plan and test results, this system will be referred to as the MFD/ΔA configuration.

As indicated in Figure 10, the MFD/ΔA configuration is defined by the following components:

(1) MFD--Pitch and roll steering commands are based on the Collins acceleration-augmented control laws for ILS tracking; in the go-around mode (TOGA button depressed), a modified pitch steering command is provided based on the SRI go-around guidance computation.

(2) Thrust Command--The Fast/Slow indicator provides speed commands based on the Collins algorithm with compensation for diminishing headwinds (MFDT-2); on go-around, the Fast/Slow indicator displays angle-of-attack error.

(3) Go-Around Advisory--A light mounted on the glare shield, above the ADI, illuminates when the acceleration margin algorithm calls for a go-around.

(4) Moving Tape Display--Analog displays of airspeed, ground speed, and acceleration demand are presented on the Kollsman moving tape instrument, rather than on conventional dial-pointer displays.

2. Comparison Systems

In order to obtain more complete information on the MFD/ΔA test system, its performance in support of precision ILS approach operations was contrasted with two comparison systems. The first comparison system was simply the unmodified DC-10 flight instruments and approach management technique and is referred to as the "baseline" (BL) system. The second comparison system represents an alternative way of presenting

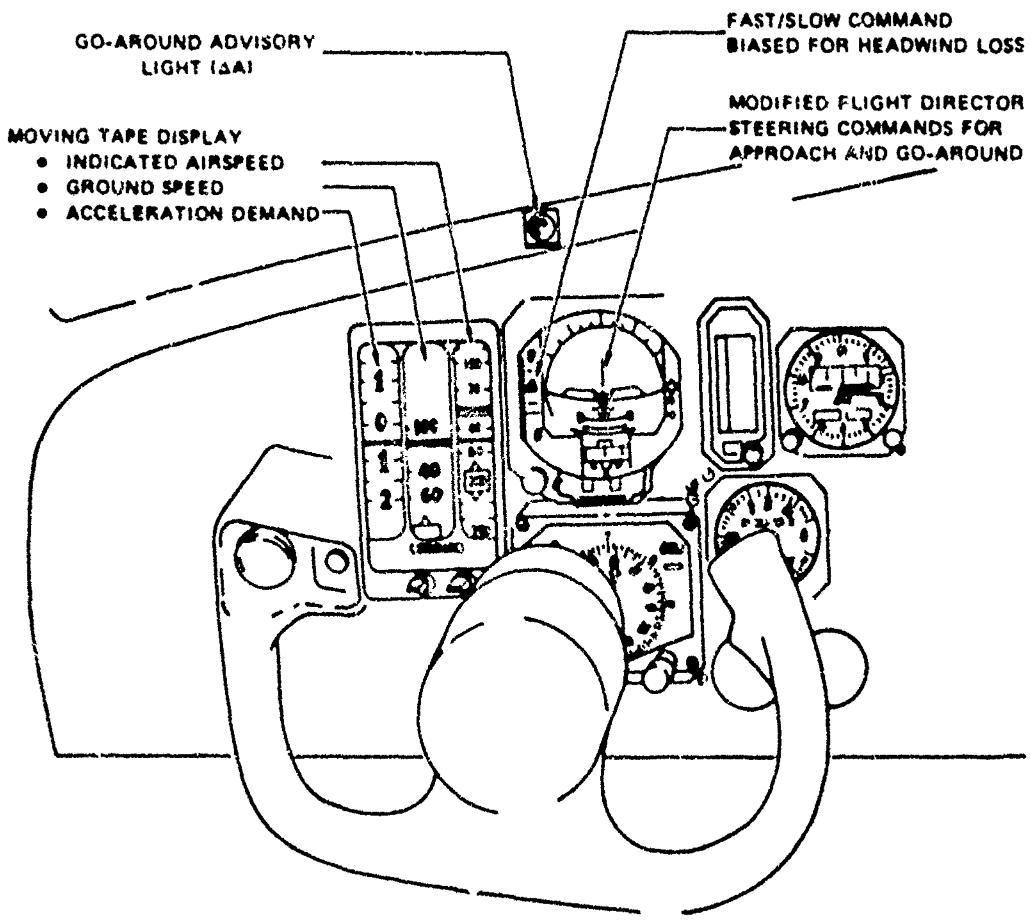


FIGURE 10 SUBJECT PILOT'S INSTRUMENT PANEL CONFIGURATION FOR THE MFD/ΔA TEST SYSTEM

speed management and go-around advisory information, and is referred to as the GNS/RED configuration.

The instrument panel configuration for the GNS/RED system is shown in Figure 11. The distinguishing components of this system, also described in Section III, are:

(1) The two-pointer display of airspeed and ground speed.

(2) Modification of the Fast/Slow indicator to present ground speed error or airspeed error.

(3) Standard DC-10 flight director for approach; modified go-around guidance is available on the pitch steering command when TOGA is depressed.

(4) Wind condition and go-around advisories are displayed on the Run Evaluation Display (RED), an alphanumeric readout located just above the radio and barometric altimeters.

The instrument panel configuration used for the baseline condition was the same as that shown in Figure 11 with the RED covered. On BL runs the ground speed needle on the two-pointer display was biased to a value beyond the normal range of approach speeds and was not used. In addition, flight director steering commands and the Fast/Slow indicator were based on standard DC-10 specifications for both approach and go-around guidance.

C. Evaluation Plan

1. Subject Pilots

Ten currently active transport pilots were recruited by FAA to serve as subject pilots in this study. Seven were DC-10 qualified airline captains, representing six major domestic carriers. Their total flying time as pilot in command ranged from 5000 to 28,000 hours and averaged 14,700 hours. Their time in the DC-10 ranged from 0 (L-1011 pilot) to 3500 hours and averaged 1084 hours. Four of these pilots had participated in earlier phases of this simulation program and were thereby exposed to some of the aiding systems and wind shears. The three non-airline pilots were two FAA pilots with approximately 4000 hours each, and a Boeing engineering test pilot with 9700 hours. Only one of these pilots was DC-10 qualified (75 hours) and two of the three were subject pilots in earlier tests.

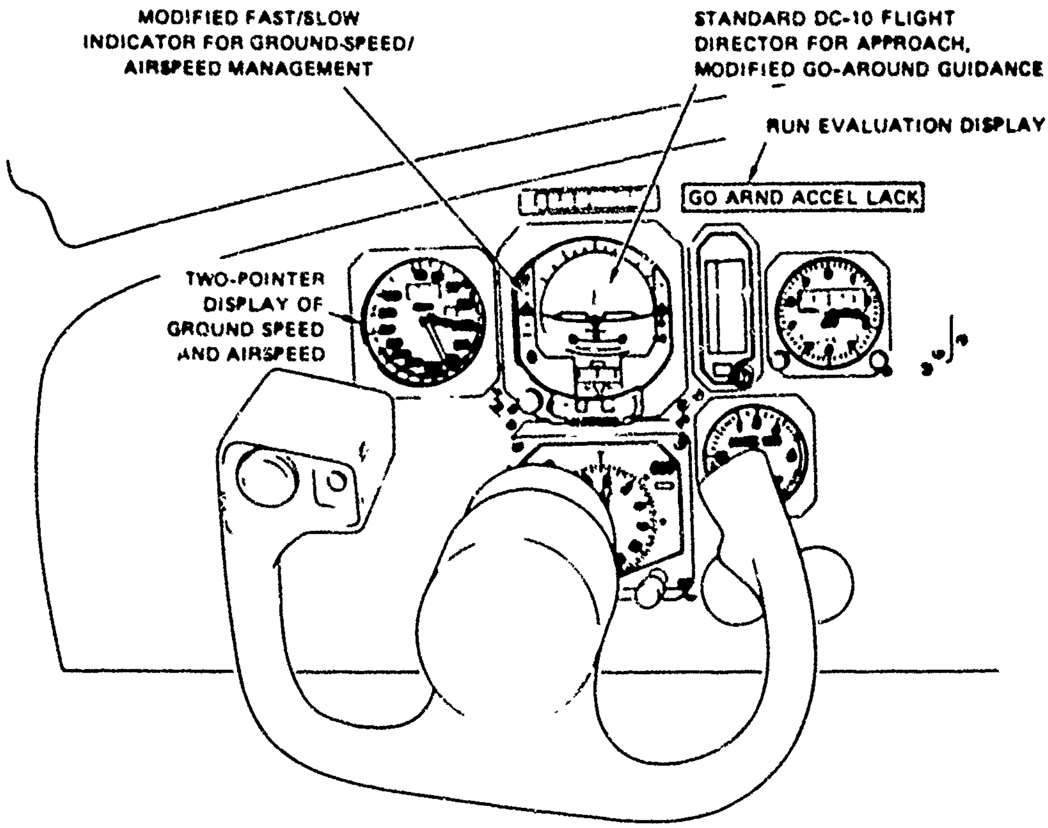


FIGURE 11 SUBJECT PILOT'S INSTRUMENT PANEL CONFIGURATION FOR THE GNS/RED TEST SYSTEM

2. Experimental Design

The principal objective of the precision approach test was to demonstrate the potential performance of the selected aiding systems in coping with low-level shear of various types and levels of severity. As indicated in the preceding section, the subject pilots were exceptionally well qualified and it was assumed that their performance of the approach management task, using the experimental aiding systems, would provide a sound basis for estimating the operational potential of these systems. The primary basis for making this estimate was the data recorded on approach outcomes for encounters with shear conditions classified in previous hazard definition studies as representing "low," "moderate," and "high" levels of severity.

Objective approach outcome data were supplemented by pilot critiques of the aiding systems and their acceptability for use in regular airline operations. In this test, primary emphasis was placed on the evaluation of the MFD/ΔA system. However, the design also provided for a comparative evaluation of the MFD/ΔA system with the DC-10 baseline system, and with the alternative aiding concept represented in the GNS/RED system.

The data collection plan adopted for this test is shown in Table 6. Each subject pilot was assigned to fly three sessions in the simulator and used a different panel configuration in each session. As Table 6 shows, the plan did not provide for complete counterbalancing of pilot exposure to the aiding systems, to compensate for carry-over effects (i.e., learning, motivation, fatigue, etc.) from one session to the other. This was precluded by the time required to reconfigure the instrument panel between sessions. However, note that exposure to the primary test system (MFD/ΔA) occurred in the first session on half of the sessions, and in the last session on the other half, allowing for an assessment of order effects.

A single session in the simulator consisted of a series of training runs on the assigned test system followed by a standardized series of 5 data runs. Since some of the subject pilots were already familiar with the aiding systems and with the Douglas simulator, the number of training

Table 6

TEST PLAN ADOPTED FOR THE PRECISION APPROACH STUDY

Subject Pilot	Test Conditions		
	First Session	Second Session	Third Session
1	MFD/ΔA	BL	GNS/RED
2	MFD/ΔA	BL	GNS/RED
3	MFD/ΔA	BL	GNS/ΔA*
4	MFD/ΔA	BL	GNS/RED
5	BL	GNS/RED	MFD/ΔA
6	BL	GNS/RED	MFD/ΔA
7	BL	GNS/RED	MFD/ΔA
8	BL	GNS/RED	MFD/ΔA
9	BL	GNS/RED	MFD/ΔA
10	MFD/ΔA	BL	GNS/RED

*RED not working properly--ΔA light used for go-around advisories.

runs was not the same for all pilots. The intent was to provide for a warm-up on the simulator and to then allow each pilot sufficient exposure to the aiding system to ensure correct interpretation and use of the experimental displays. The training was conducted by the project pilot in the right seat, and data runs were initiated only when both pilots were satisfied that the test system would be used correctly.

The wind-shear profiles selected for both training and data runs are identified in Table 7. The profile numbers used in this table refer the reader to corresponding profile descriptions given in Appendix A. Note that the profiles used for data runs did not include those used for training; the test data are therefore independent of the training set. The five wind profiles selected for the data run series in each session were selected from the eight shown here and always included two low-severity shears (1 and 8), one moderate shear (2 or 9), and two high-severity shears selected from those shown. The order of pilot exposure

Table 7

WIND PROFILES SELECTED FOR THE PRECISION APPROACH TEST

Wind Profile Number	Type	Severity Level
Training Runs		
0	No wind	--
3	Thunderstorm	High
7	Thunderstorm	Moderate
Data Runs		
1	Boundary layer	Low
8	Thunderstorm	Low
2	Warm front	Moderate
9	Cold front	Moderate
4	Thunderstorm	High
5	Frontal	High
6	Thunderstorm	High
10	Thunderstorm	High

to the shears on data runs was scrambled so that pilots would not be able to anticipate the shear conditions in subsequent test sessions.

This experimental design provided test data on a total of 150 approach sequences (runs) and allowed estimates of operational performance to be based on 50 runs for each of the three aiding configurations tested. These 50 runs represent 5 data runs for each pilot and break down into 20 runs each against the low- and high-severity shears and 10 runs against the moderate shear.

3. Test Procedures

The approach scenario described in Section IV-A was carried out in the same manner on all data runs in each of the three sessions. Pilots were scheduled in pairs and alternated sessions in the simulator following a master run schedule listing the sessions to be completed by each pilot for each scheduled day of testing. On the first day, a thorough project orientation briefing was presented to each pilot, covering windshear phenomena and background information on pilot technique and the prior development of the pilot aiding systems. This briefing also provided a detailed description of each component of the test systems and the ways they were intended to be used. Immediately prior to each scheduled session, the scheduled pilot was again briefed on the system he would be using in that session and on the procedures to be followed in the simulator. Debriefing sessions were conducted immediately after each simulator session to record pilot reactions and assessments of the test systems on a debriefing questionnaire.

On the BL runs, pilots were briefed to conduct each approach as they would in actual line operations and to make approach continuation/go-around decisions on the basis of their usual assessments of the flight situation. The project pilot in the right seat assumed all First Officer duties and made standard callouts of altitude, airspeed error, and ILS deviations. The pilots knew that significant shear conditions might occur on any approach (but not which shear), and were briefed to initiate a go-around promptly, if they decided to do so, and to use the procedures recommended by Douglas[6] for coping with the shear conditions encountered. The essential feature of this procedure for purposes of this test is expressed in the following excerpt:

> "Upon encountering a decreased performance shear and/or downdraft, thrust and pitch attitude should be immediately increased to maintain an acceptable airspeed and flight pattern. Power should be immediately advanced to the go-around setting if necessary, and a go-around should be initiated when this type of an encounter occurs at low altitude. Stick shaker speeds should be known for the approach and go-around configuration, and airspeed should be traded down to the stick shaker speed <u>if necessary to prevent ground impact</u>."

On MFD/ΔA and GNS/RED sessions, pilots were briefed to carefully follow the procedures prescribed for the use of these test systems. For test purposes, the use of individual pilot interpretations and techniques was discouraged. For example, pilots were briefed to accept the occurrence of a go-around advisory as mandatory, and to initiate this maneuver promptly rather than use their own discretion based on other instrument indications.

D. Results

Two kinds of measures were derived from the data recorded on each test run: (1) a system performance score, based on approach outcomes, and (2) a set of diagnostic indicators to provide additional information on these outcomes and on the performance of each component of the test systems. The systems performance scores were used as the primary basis for assessing the operational validity of the test systems, and are discussed first. A more detailed analysis of test system performance is then presented in Section IV-D-2. The presentation of results is then concluded with a discussion of subject pilot evaluations of the systems tested.

1. Approach Outcomes

A system performance score, ranging in value from +10 to -10 points, was assigned to each data run in accordance with the scheme described in Appendix D. As that discussion shows, the "system performance" score earned on each run represents the effects of aircraft performance capabilities and pilot performance of the approach management task, as well as the influence of the experimental aiding systems. However, since the aircraft, pilot, and environmental conditions (wind profiles, weather, and so forth) were the same for all the test systems, their effects are a common factor and the effect of the aiding system was isolated and assessed by comparisons with baseline performance.

Table 8 presents a tabulation of the number of approach outcomes in each of the four possible performance classes for each of the test systems. This tabulation is based on 50 approach outcomes for each test system and reflects performance across all of the wind-shear profiles and levels of severity. The average performance score may thus be construed as an overall index of system performance. A more detailed breakdown of the approach outcomes is given in Appendix G.

Table 8

DISTRIBUTION OF DATA RUNS BY SYSTEM PERFORMANCE SCORE FOR EACH TEST SYSTEM*

System	Number of Approaches				Performance Score Averaged Over Runs
	Go-Arounds		Touchdowns		
	Successful	Unsuccessful	In-limits	Out-of-limits	
Baseline	22	6	11	11	-0.02
MFD/ΔA	24	0	21	5	6.60
GNS/RED	28	0	12	10	2.68

*Based on data from 50 runs for each test system.

The average performance scores for the three test systems are plotted in Figure 12. The MFD/ΔA system performed significantly better than GNS/RED, which in turn was much better than BL. Further, the MFD/ΔA score is quite close to the expected top level of performance (8.0, as noted in Appendix D) corresponding to the score that would be obtained in a comparable flight simulation test with no wind shear. The MFD/ΔA system therefore provided both a significant relative improvement over BL, and an absolute performance acceptably close to the top expected value.

A more graphic presentation of the overall performance of the test systems is given in Figure 13. This plot breaks the data runs down by wind-shear severity and gives the mean performance score for each test system. The mean performance scores are based on the number of data

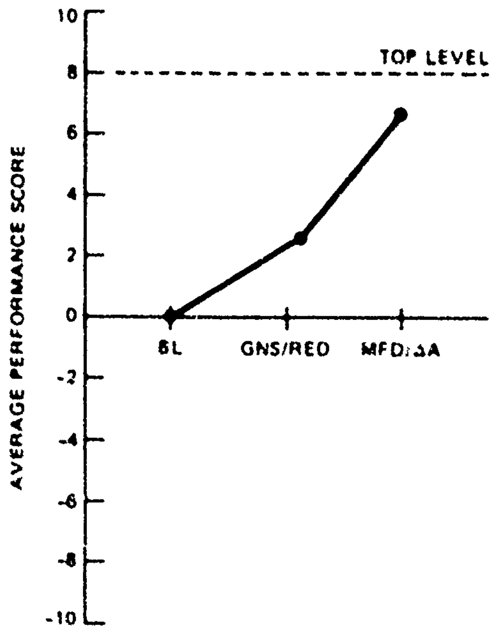


FIGURE 12 SYSTEM PERFORMANCE — PRECISION APPROACH

runs (n) shown for each severity level, and were derived according to Appendix D. This plot shows that all of the 20 runs flown with the MFD/AA system against high-severity shear conditions resulted either in a successful go-around or a within-limit touchdown. Figure 13 also shows a substantial improvement in performance on low and moderate wind shears for the MFD/AA system, and no substantial improvement over BL for the GNS/RED system on these shear conditions.

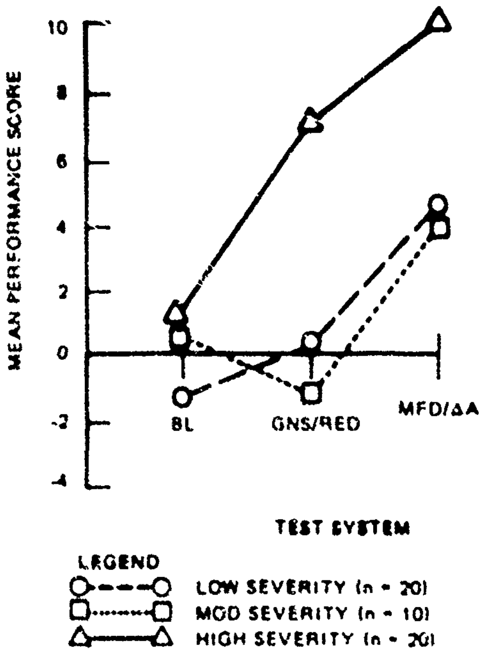


FIGURE 13 CONTRAST IN PERFORMANCE FOR EACH LEVEL OF WIND-SHEAR SEVERITY — PRECISION APPROACH

When mean performance scores are examined for each of the wind-shear profiles, as shown in Figure 14, a marked difference is apparent in the effects of individual wind profiles on approach outcomes and on the comparisons across aiding systems. Note that all of the BL runs against wind profile 4 were scored a -10 and that all were +10 on the remaining high-severity shear conditions. As noted earlier, the MFD/ΔA system produced +10 scores on all of the high-severity shears; this level of performance was matched by the GNS/RED system on all but wind profile 5. Figure 14 also shows that MFD/ΔA system performance was consistently batter than BL on low- and moderate-severity shear conditions. The comparatively lower scores indicated for this system on low- and moderate-severity shears is attributable, in part, to the penalties imposed on go-around on moderate shears (a go-around advisory was generated on all approaches against wind profile 2).

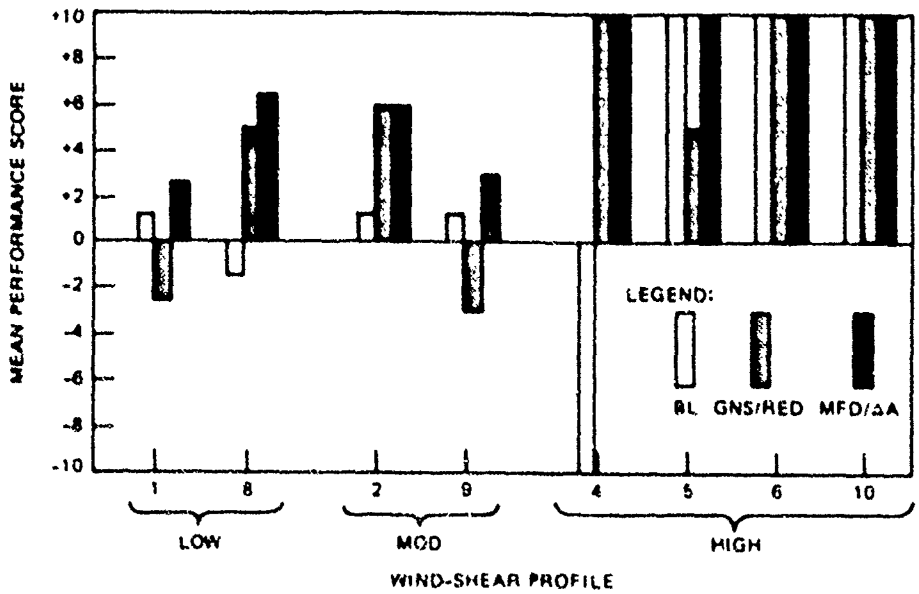


FIGURE 14 CONTRAST IN PERFORMANCE FOR INDIVIDUAL WIND-SHEAR PROFILES — PRECISION APPROACH

The statistical significance of recorded differences in performance scores across all three test systems was tested using the Friedman two-way analysis of variance by ranks.[6] This test is based on differences in the performance scores earned by individual subject pilots when the different aiding systems were used. The test indicated a probability of less than .01 that differences in pilot performance were independent of the test systems used. A subsequent test of differences between the performance of the BL system and the MFD/AA (Wilcoxon matched-pairs signed-ranks test)[7] was also significant at less than the .01 probability level.

2. Analysis

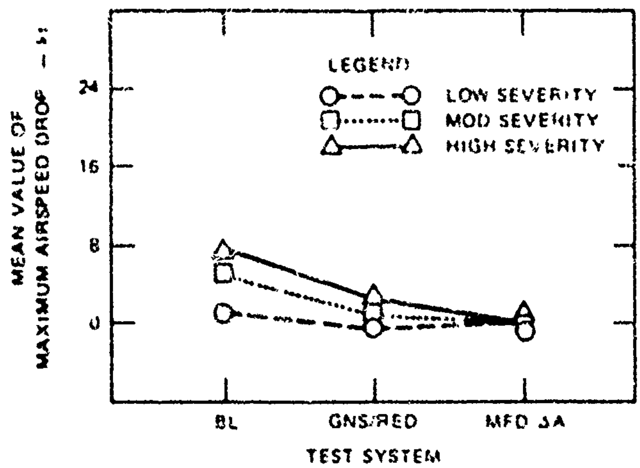
Airspeed management, flight path control and the timely execution of a go-around, when necessary, are the basic elements of the approach management task, and the various components of the aiding systems were expected to support and enhance pilot performance of these task elements. The results presented in this section provide an indication of how well these task elements were supported by each of the test systems. In practice, the approach management task must be accomplished in an integrated manner and the interacting effects of the three task elements cannot be cleanly distinguished; the data presented here should be interpreted with that in mind.

a. Airspeed Management

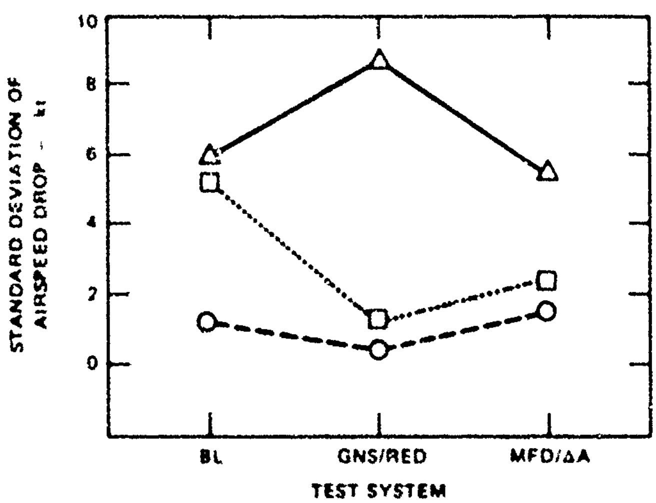
The airspeed management technique embodied in the MFD/ΔA (MFDT-2) and GNS/RED systems (airspeed/ground speed error) were designed to minimize airspeed loss with respect to desired approach speed (V_{APP}) by calling for an airspeed pad based on a minimum preplanned ground speed (see Section III for details). The summary data plot in Figure 15 shows that both of the test systems were highly effective in minimizing airspeed loss on all levels of shear severity. The coded data points given in Figure 15(a) are the maximum drop in airspeed below V_{APP}, over the 500-to-100-foot approach segment, averaged across all runs against the designated shear severity levels (n = 20 for low- and high-severity shears, and n = 10 for moderate shears). As indicated, mean values converged to zero airspeed drop for the MFD/ΔA system.

The variability around these means is plotted separately in Figure 15(b) to reduce clutter. This plot shows that one-sigma (standard deviation) values were below 10 knots under all test conditions and that they were less than 6 knots for the MFD/ΔA. Differences in variability appear to be attributable to the severity of the shear and are not substantially different for the three aiding systems.

The role of the ground speed management technique in controlling airspeed loss is shown in Figure 16. The data points in this plot are the maximum drop in ground speed below the preselected minimum for each wind profile (GNS_{ref}), again averaged over data runs under the three levels of shear severity. The mean values of less than 5 knots for the two test systems indicate that the subject pilots applied these techniques



(a) MAXIMUM DROP IN AIRSPEED OVER THE 500-TO-100-FOOT PRECISION APPROACH SEGMENT



(b) VARIABILITY IN MAXIMUM AIRSPEED DROP FOR MEAN VALUES PLOTTED ABOVE

FIGURE 15 CONTRAST IN AIRSPEED MANAGEMENT FOR EACH LEVEL OF WIND-SHEAR SEVERITY — PRECISION APPROACH

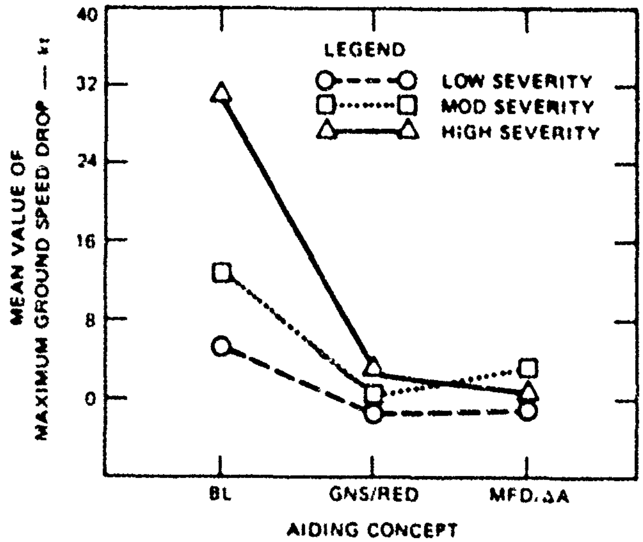
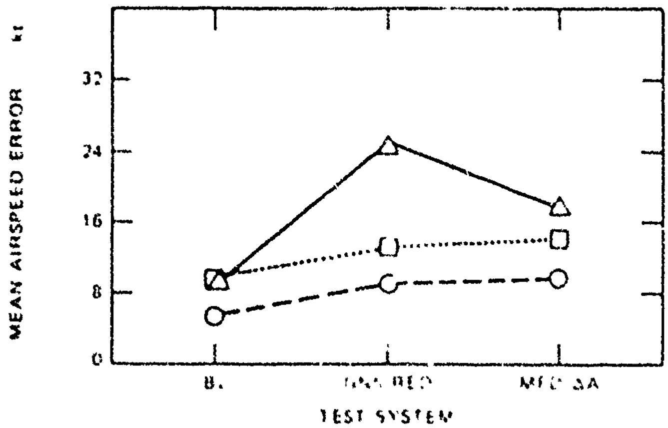


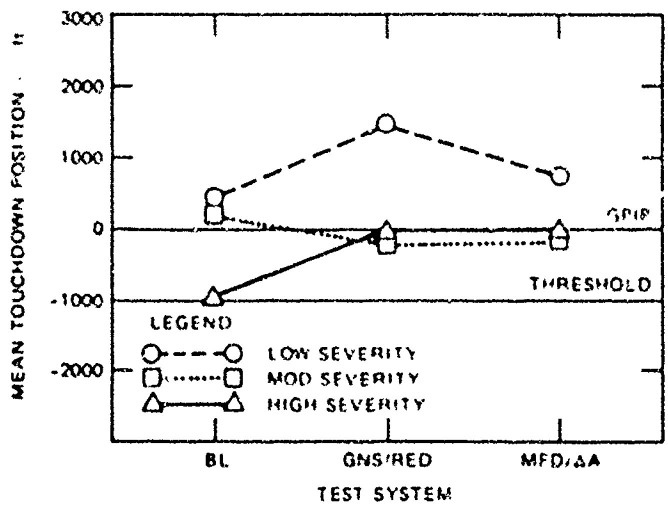
FIGURE 16 MAXIMUM DROP IN GROUND SPEED ON THE 500-TO-100-FOOT APPROACH SEGMENT — PRECISION APPROACH

effectively--i.e., ground speed was maintained at or above reference. Under BL conditions, ground speed varied with the severity of the shear, as expected, and averaged 30 knots below reference on the high-severity profiles.

A major concern relating to the ground speed technique is that the high approach airspeeds required to maintain GNS_{ref} might lead to unacceptably high speeds going into the landing maneuver, with subsequent adverse effect on touchdown position (e.g., long landings). Figure 17(a) indicates that mean airspeeds were somewhat higher than baseline when this technique was used on high-severity shears. In Figure 17(b) we show the average touchdown positions relative to the glide path intercept point (GPIP) under corresponding conditions. The data show that mean touchdown positions were very close to the GPIP for the high-severity shears when the ground speed technique was used, with no tendency toward long landings. One-sigma deviations in touchdown position for these



(a) RMS AIRSPEED ERROR OVER THE 500-TO-100-FOOT SEGMENT



(b) TOUCHDOWN POSITION ALONG THE RUNWAY, AVERAGED OVER DATA RUNS FOR EACH LEVEL OF SHEAR SEVERITY

FIGURE 17 CONTRAST IN AIRSPEED MANAGEMENT AND TOUCHDOWN POSITION — PRECISION APPROACH conditions were 292 feet for the GNS/RED system and 688 feet for the MFD/ΔA. Note that baseline touchdowns for the high-severity shears tended to be dangerously short.

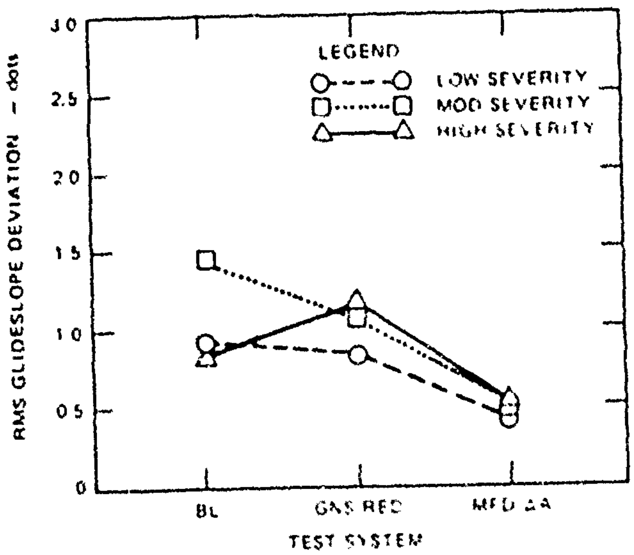
b. Flight Path Control

Summary data on the accuracy of glide slope and localizer tracking are plotted in Figure 18. The data points in these plots are mean values of ILS deviations recorded on the 500 to 100-foot approach segment for data runs under each level of shear severity. As shown in Figure 18(a), glide slope tracking accuracy improved on all levels of shear severity when the modified flight director was used (MFD/ΔA system). A similar plot of the contrast in localizer tracking accuracy, shown in Figure 18(b), indicates a slight trend toward more accurate tracking when the MFD is used, but the differences are not of practical significance.

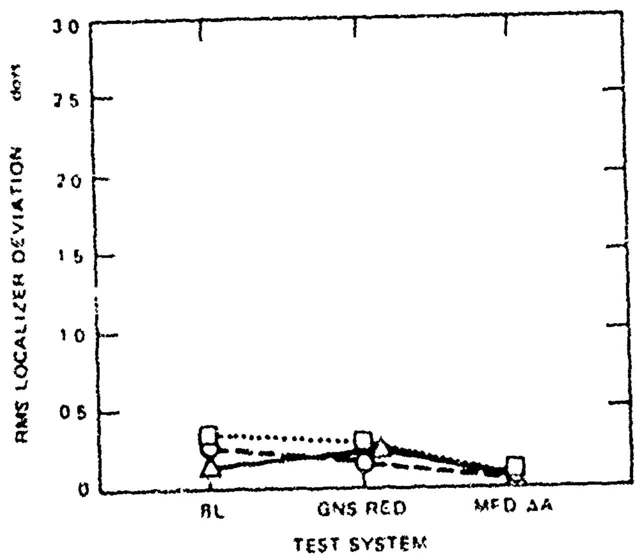
An improvement in flight path control attributable to the MFD is also shown in Figure 19. The data points in this plot show the number of approaches, relative to the total number attempted, that were within acceptable flight path offset and rate-of-sink limits at the Inner Marker position. For this assessment, limiting values for flight path offsets were ±28 feet (two dots) for glide slope, and ±75 feet for localizer (nominal runway width); the rate-of-sink limit was 1500 feet/min. The data show a substantial increase in the percentage of within-limit approaches for the MFD/ΔA system, particularly on low and moderate shears.

c. Go-Around Performance

Earlier simulation studies pointed up the need for additional assistance to the pilot for determining when a go-around would be the best course of action on the more severe wind-shear conditions. In the primary test system, this assistance was provided in the form of an acceleration margin (ΔA) display and go-around advisory light. In the baseline and GNS/RED systems the ΔA advisory was not used for deciding to go-around, but the run data recorded the event if the ΔA criterion was met.



(a) GLIDE SLOPE TRACKING ACCURACY FOR THE 500-TO-100-FOOT APPROACH SEGMENT



(b) LOCALIZER TRACKING ACCURACY FOR THE 500-TO-100-FOOT APPROACH SEGMENT

FIGURE 18 CONTRAST IN FLIGHT DIRECTOR SUPPORT OF FLIGHT PATH CONTROL — PRECISION APPROACH

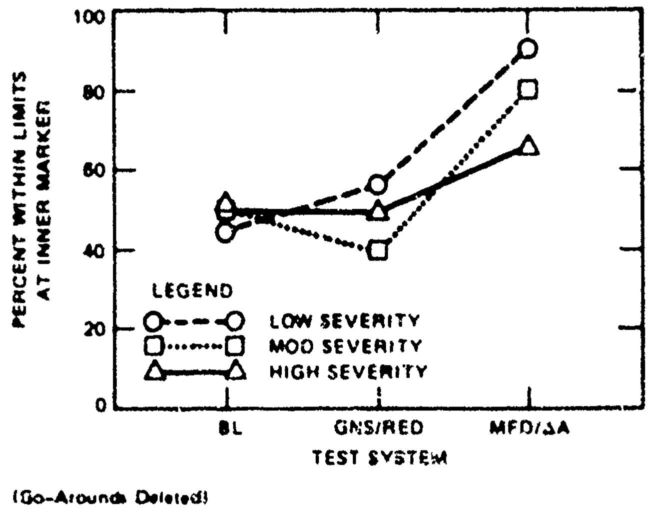


FIGURE 19 CONTRAST IN FLIGHT PATH OFFSETS AT THE INNER MARKER POSITION — PRECISION APPROACH

The performance of this go-around advisory system for each of the wind-shear profiles applied during the test runs is summarized in Table 9. This tabulation is based on 147 data runs and thus includes data runs under other conditions as well as those for the MFD/ΔA. The count entered in the "Number of Advisories" column is the number of times ΔA reached its critical value (see Section III for description) and is therefore the number of times an advisory was actually displayed or would have been displayed. The occurrence of this event was recorded on each run, whether the advisory was displayed or not, and this additional datum is reported for the more complete information it provides.

Table 9 shows that advisories were associated with high-severity shears, except for profile 5, in every instance. Data on approach

Table 9

TABULATION OF GO-AROUND ADVISORIES BY WIND-SHEAR PROFILE FOR PRECISION APPROACH DATA RUNS (N = 147)*

Wind Profile Number	Number of Runs	Number of Advisories	Percent of Runs
Low Severity			
1	29	5	17.2
8	30	0	0
Moderate Severity			
2	13	11	84.6
9	16	0	0
High Severity			
4	23	23	100
5	12	0	0
6	10	10	100
10	14	14	100

*Data missing on three test runs.

outcomes show that 9 of the 12 runs against profile 5 resulted in a landing and that all but one of these landings were within limits. The data may therefore be construed as showing the AA technique to be remarkably consistent and effective in providing warning for high-severity shears.

The absence of any advisory on profiles 8 and 9 also indicates that the AA system reliably distinguished low- and moderate-severity shears and would not issue false alarms in these instances. However, profile 1 has been shown to be negotiable by most pilots in several earlier studies, and the five advisories associated with this shear condition may be construed as false alarms. The very high percentage of advisories for profile 2 is more difficult to interpret. Only 1 of 13 data runs on this profile resulted in a landing, and that touchdown was out of limits, with an unacceptably high lateral velocity (23 feet/s), and under baseline conditions (no display of advisories) the pilot elected to go-around on 4 of the 5 runs. It would thus appear that go-around advisories are justified on this profile and that the high percentage of advisories recorded indicate appropriate system performance.

Another aspect of the performance of the ΔA system is shown in Figure 20. This summary data plot shows that advisories were issued early on the high- and moderate-severity shears, and illustrates the predictive nature of the ΔA advisory--i.e., the advisory is issued before the major effect of the shear is encountered. Data points for BL runs were substantially the same as those shown for the test systems, but were omitted on this plot because advisories were not displayed under this condition. The data for low-severity shears refer to profile 1, as indicated in Table 9, and show that this condition (rapid head-wind shearout close to the ground) was not predicted by the system, and that when an advisory was issued the aircraft was hazardously low.

The foregoing interpretation is supported by the data plotted in Figure 21 on the execution of the go-around maneuver. The data points here provide a rough indication of the success of the go-around by showing the lowest altitude to which the aircraft descended during the go-around attempt. With no advisories available on the BL condition, go-arounds tended to be initiated at very low altitudes, while the aircraft was in the midst of the shear encounter. The MFD/ΔA system provides substantial protection against this hazardous outcome for high- and moderate-severity shears, with go-arounds completed at or above 400 feet in the typical case.

The overall effect of having the go-around advisory displayed, and of the availability of modified climbout guidance for the go-around maneuver, is indicated in Table 10. This tabulation shows the number of go-arounds attempted under each test condition and the number of these attempts that were successful; the percentages shown in parentheses relate the number of go-arounds to the corresponding number of data runs for each test condition and indicate the success rates for these go-around counts. The reader will recall that under baseline conditions, no advisories were displayed.

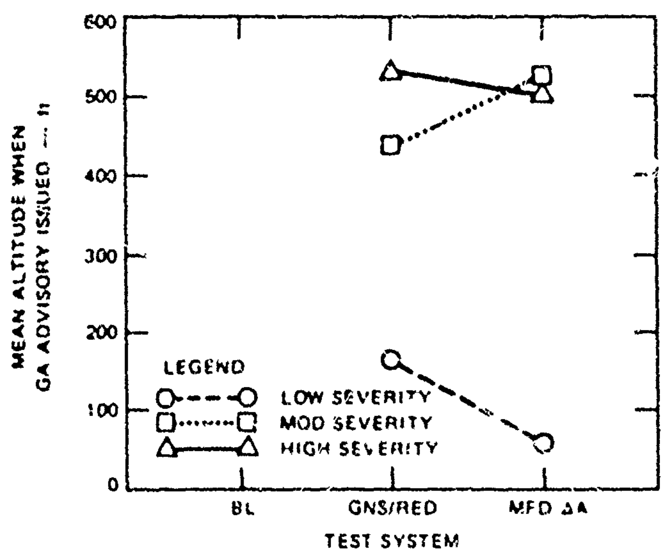


FIGURE 20 AVERAGE ALTITUDES AT WHICH GO-AROUND ADVISORIES WERE ISSUED — PRECISION APPROACH

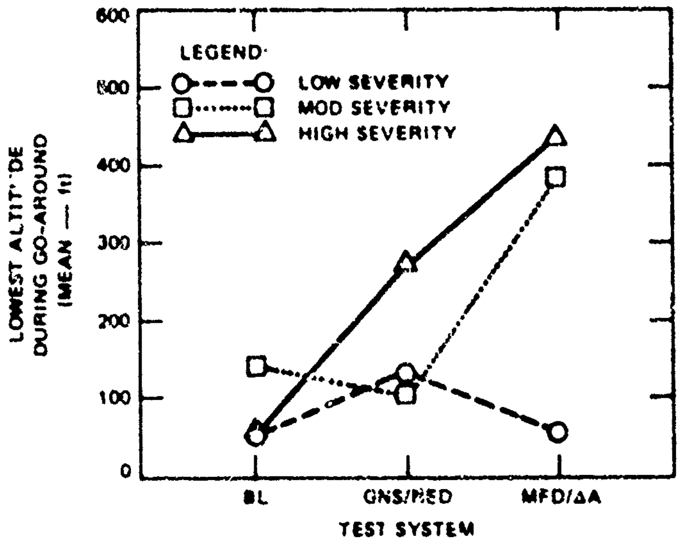


FIGURE 21 CONTRAST IN GO-AROUND PERFORMANCE — PRECISION APPROACH

Table 10

TABULATION OF GO-AROUNDS BY WIND-SHEAR SEVERITY FOR EACH TEST SYSTEM--PRECISION APPROACH

Test Condition	Number of Runs	Number of Go-Arounds	Number Successful
Baseline			
Low	20	7 (35%)	7 (100%)
Moderate	10	7 (70%)	7 (100%)
High	20	14 (70%)	8 (57%)
MFD/AA			
Low	20	2 (10%)	2 (100%)
Moderate	10	5 (50%)	5 (100%)
High	20	17 (85%)	17 (100%)
GNS/RED			
Low	20	9 (45%)	9 (100%)
Moderate	10	4 (40%)	4 (100%)
High	20	15 (75%)	15 (100%)

The data show a reduction in the number of go-arounds for low- and moderate-severity shears, and some increase in high-severity shears, when the MFD/AA system is used. The important number to note in this table is the 100% success rate for the MFD/AA system under high-severity shear conditions and its contrast with the 57% success rate for the BL system. Since "unsuccessful" go-arounds are crashes in this study, the success rate shown for the MFD/AA system represents a substantial improvement in safety. The performance of the GNS/RED system also shows this enhancement of safety. While the number of go-arounds does not differ substantially from BL for this system, the 100% success rate on go-arounds from high-severity shear encounters shows the same elimination of the unsuccessful go-arounds as that obtained with the MFD/AA system.

3. Pilot Evaluations

During the debriefing sessions following each data run series in the simulator, subject pilots completed a questionnaire designed to elicit their reactions to the test system they had just been exposed to and to record their critique of its various functional components. At the end of the final session, the pilots completed a short extension of this questionnaire to provide an overall indication of their assessment of the test systems and the simulation. The questionnaire is reproduced in Appendix E, and a tabulation of subject pilot responses to each question is provided. The highlights of those responses are presented here.

a. General Evaluation

Both the MFD/ΔA and the CNS/RED test system were seen as potential solutions to the problem of low-level wind shear, based on the responses of 8 of the 10 pilots. The other two responses were more positive, indicating that the two test systems were acceptable solutions. In contrast, half of the pilots rated the BL system as "no solution". Nine pilots judged the simulated wind-shear conditions to be "very realistic" or "about right", and only one considered them to be "much too severe". All 10 pilots saw the overall simulation as "good" (6) or "very good" (4).

b. Ground Speed Technique

As in earlier studies, pilot evaluations of this technique were very positive. Nine felt that the concept was "excellent" and all 10 pilots indicated that they would like ground speed displayed on the approach, that the technique was practical for routine operations, and that it should be taught to all pilots. Only 2 of the 10 pilots found the two-pointer display to be confusing, and 7 preferred this type of presentation over the moving tape display used with the MFD/ΔA system. This preference probably reflects the influence of extensive prior experience with the pointer-scale type of display for primary flight instruments. Six pilots reported prior experience with vertical displays, but for engine instruments rather than flight instruments. It is interesting, however, that 4 pilots indicated a preference for the tape instruments at the end of the study.

All 10 pilots judged the incorporation of the additional ground speed reference into the Fast/Slow (F/S) indicator to be of value, with 6 indicating that it was "great" and 4 indicating that it "helps at times". Most of them (6) reported using the F/S indicator as a secondary source to the airspeed indicator for speed management on approach. Eight judged the F/S as "excellent" for implementing the ground speed technique.

c. Modified Flight Director

Pilot assessments of the Collins modification to flight director steering commands (MFD) was also highly positive, as it has been in earlier evaluations. All 10 pilots rated it as "better" than the standard flight director, and 9 of them preferred the MFD for severe wind conditions. Four pilots preferred the MFD "at all times", while 5 would want it in the airplane "only for tough, turbulent approaches". A majority ([illegible]) wanted a switch that would allow them to select the MFD or use the standard flight director.

Steering commands were not judged to be excessively active by most pilots, but 4 of the 10 felt that they were not able to fly the approach as precisely as they would like. However, 6 pilots judged the MFD as "smooth enough" for day-to-day operations, and all 10 said it helped them to fly a more precise approach.

d. Go-Around Advisories and Climbout Guidance

Eight pilots said they would like to have the acceleration margin (AM) instruments in their cockpit, and the ninth said he would like it if he could have the light only. All of them said they accepted the light as a valid go-around advisory "most of the time" (7) or "all of the time" ([illegible]). With one exception, they reported that they used the moving tape display of AM to monitor thrust requirements (one did not use this instrument). They felt that this display provided a good clue to power needs and that the light came on "soon enough" for a timely execution of the go-around maneuver.

In response to a general question on go-around technique, 6 of the 10 pilots said they believed it would be safe to trade off airspeed for climb performance down to stick shaker speed, if necessary. Three others would not accept an airspeed less than 10 knots below V_{ref}, and one pilot opted for 15 knots below. All of the 10 pilots indicated that they wanted flight director assistance for the go-around maneuver and that the modified pitch steering commands were "very helpful" for climbout guidance.

Pilot reactions to the Run Evaluation Display (RED) were also positive, with some reservations and mixed feelings expressed. Most of them (8) indicated that they liked the go-around advisory features, and 6 out of 10 said they would prefer to be aided in their decision by a "black box". However, 3 pilots would not express a preference on this. Only 6 would state positively that they would like to have the RED in the cockpit; of the 10, 7 judged it to be "helpful at times", and 2 judged it as "very helpful". The feature preferred by most pilots (8) was the go-around advisories, and 5 pilots also indicated that information on surface wind conditions was helpful. With one exception (no response), the pilots said that they had the first officer monitor the RED and advise them of any significant display events.

V NON-PRECISION APPROACH STUDY

A. Situation Simulated

The simulation scenario adopted for validation testing of the MFD/ΔA and GNS/RED systems on the non-precision approach was similar in many respects to the precision approach scenario described in Section IV. A manual flight director approach was flown, and run initiation and termination conditions were the same. The simulated aircraft configuration, wind-shear profiles, runway used, and ambient conditions (i.e., field elevation 5,300 feet and 95°F air temperature) were also the same. The principal differences were that a "synthetic glide path," as described in Section III, was used for vertical guidance rather than the ILS glide slope, and that ceiling and visibility conditions were raised to non-precision approach minimums (400 feet breakout altitude and 5000 feet RVR). Localizer guidance was available using the same ILS beam simulation as that used for the precision approach.

For the baseline condition, it was necessary to modify this scenario to accommodate standard DC-10 procedures for a non-precision ILS approach (no glide slope). With no synthetic glide path available, approach sequences were initiated at 1800 feet AGL with the aircraft in level flight and approaching the outer marker with landing gear down, flaps at 22°, and speed stabilized on the minimum maneuvering airspeed for this configuration. On arrival at the marker, the pilot transitioned to a steep descent (approximately 1000 ft/min), called for landing flaps (50°), and began a final descent to the minimum descent altitude (MDA). Aircraft landing gross weight and ambient conditions were the same as those adopted for the precision approach test. Most of the DC-10 qualified pilots elected to use the flight guidance system in the "vertical speed" mode, and thus used flight director pitch steering commands to maintain the 1000 feet/min initial descent.

After leveling off at the MDA (350 feet AGL), the aircraft proceeded to a DME-defined visual descent point (VDP) and, following visual acquisition of the runway environment, established a final glide path to the runway and completed the approach by external visual reference. If the runway environment was not in sight at the VDP, or the approach situation was otherwise unacceptable to the pilot, a go-around was initiated. The non-precision approach was terminated in the same manner as the precision approach--i.e., shortly after touchdown, after a successful go-around, or after a crash.

B. Systems Tested

The MFD/AA was again the test system of primary interest, and the subject pilot's instrument panel configuration for this test condition was the same as that shown in Figure 10. The comparison system was GNS/MF/R, the same as GNS/RED except that the modified flight director steering commands on approach were used instead of the BL flight director commands; the panel configuration did not differ from the arrangement shown in Figure 11. Except for the pitch steering command, the functional components of these test systems were also the same as described in Section IV. The important difference, as indicated above, was that pitch steering commands were based on the "Synthetic Glide Path" computation described in Section III, rather than on ILS glide slope deviation. The BL system was the same in all respects as that described earlier for the precision approach study.

C. Evaluation Plan

1. Subject Pilots

Ten additional transport pilots were recruited by FAA to serve as subject pilots in this study. This group included six airline pilots, from three different carriers, with an average total flying time of more than 20,000 hours. Four of these pilots were DC-10 qualified and their time in the DC-10 averaged 1800 hours. The group also included two engineering test pilots, both with about 9000 hours total time; one of these pilots, from Douglas, had 2100 hours in the DC-10. The two remaining pilots were U.S. Air Force pilots, with an average command-pilot time of 4400 hours. Four of these 10 pilots had participated in earlier phases of the wind-shear program and were thus familiar with some of the aiding systems and wind shears.

2. Experimental Design

The objectives and the approach to aiding system evaluation followed a pattern similar to that described for the precision approach. The data collection plan for the non-precision approach study is shown in Table 11. Subject pilots are designated by numbers 11 through 20 to distinguish them from the first 10. Each pilot was scheduled for three sessions in the simulator and was exposed to the three different aiding conditions in the order shown. Note that exposure to the display conditions was again partially counterbalanced to control for order effects.

Run schedules for each session provided for familiarization and training during the first part of the session and then a series of five data runs. Wind-shear profiles used for training and data runs were the same as those identified earlier in Table 7. The order of pilot exposure to the shear conditions on the data runs was again scrambled so that pilots would not be able to anticipate particular wind shear effects.

Test procedures, pilot scheduling, and data reduction and analysis were the same as those described in Section IV for the precision approach study. Test data were obtained on a total of 140 approach sequences, and estimates of the operational performance of the test systems on the non-precision approach were based on 50 runs under BL and MFD/ΔA conditions, and on 40 runs using the GNS/MF/R system. Ten data runs were lost for the latter system because the RED unit was not working properly for the test sessions on the first pair of pilots.

Table 11

TEST PLAN ADOPTED FOR THE NON-PRECISION APPROACH STUDY

Subject Pilot	Test Condition		
	First Session	Second Session	Third Session
11	MFD/ΔA	BL	GNS/MF/R*
12	MFD/ΔA	BL	GNS/MF/R*
13	MFD/ΔA	BL	GNS/MF/R
14	MFD/ΔA	BL	GNS/MF/R
15	BL	GNS/MF/R	MFD/ΔA
16	BL	GNS/MF/R	MFD/ΔA
17	BL	GNS/MF/R	MFD/ΔA
18	BL	GNS/MF/R	MFD/ΔA
19	BL	GNS/MF/R	MFD/ΔA
20	BL	GNS/MF/R	MFD/ΔA

*RED not working properly during these two sessions; data were not used.

D. Results

1. Approach Outcom...

A tabulation of the number of non-precision approach outcomes in each of the four possible system performance classes is given in Table 12 for each test system. A more detailed breakdown is given in Appendix C. Note that evaluation of the GNS/MF/R system is based on 40 runs (8 pilots) because ten data runs were invalid due to RED malfunction.

Table 12

DISTRIBUTION OF DATA RUNS BY SYSTEM PERFORMANCE SCORE FOR EACH TEST SYSTEM--NON-PRECISION APPROACH

System	Number of Approaches				Total Runs	Performance Score Averaged Over Runs
	Go-Arounds		Touchdowns			
	Successful	Unsuccessful	In-limits	Out-of-limits		
Baseline	25	3	15	7	50	1.90
MFD/ΔA	25	1	23	1	50	6.90
GNS/MF/R	15	-	19	6	40	4.17

*Based on 50 data runs for BL and MFD/ΔA and on 40 runs for the GNS/MF/R system (see Section V-C); thus, percentages are comparable for GNS/MF/R, but counts are not.

The trend in performance scores is similar to the results obtained on the precision approach, with an improvement shown for the MFD/ΔA; GNS/MF/R performance is again about midway between BL and the MFD/ΔA.

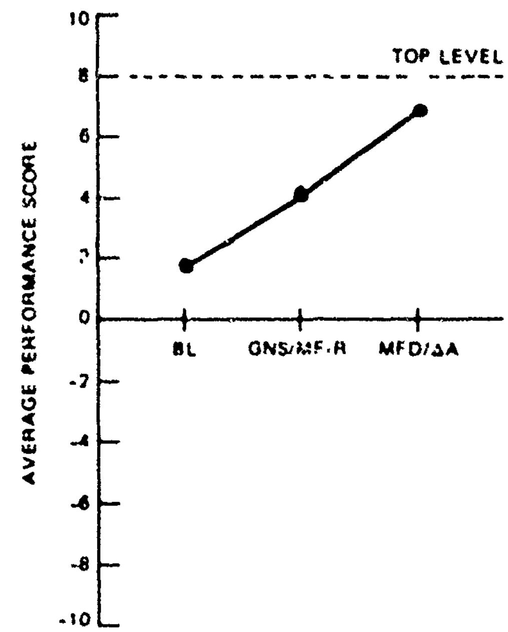


FIGURE 22 SYSTEM PERFORMANCE — NON-PRECISION APPROACH

The average performance scores for each of the test systems are plotted in Figure 22. While the GNS/MF/R score is somewhat better than BL, the MFD/ΔA system is significantly better than both. Note also that in absolute terms the MFD/ΔA score is close to the 8.0 top level, which corresponds to the score that would be expected in a comparable DC-10 simulation test with no wind shear (Appendix D). These data show that MFD/ΔA both provides a significant relative improvement over BL and performs in an absolute sense acceptably close to the expected top score.

A breakdown of mean performance scores for each level of wind-shear severity is plotted in Figure 23. This plot shows a more substantial improvement in performance for the MFD/ΔA system on low and moderate shears, over BL procedures, than that obtained in the precision approach study.

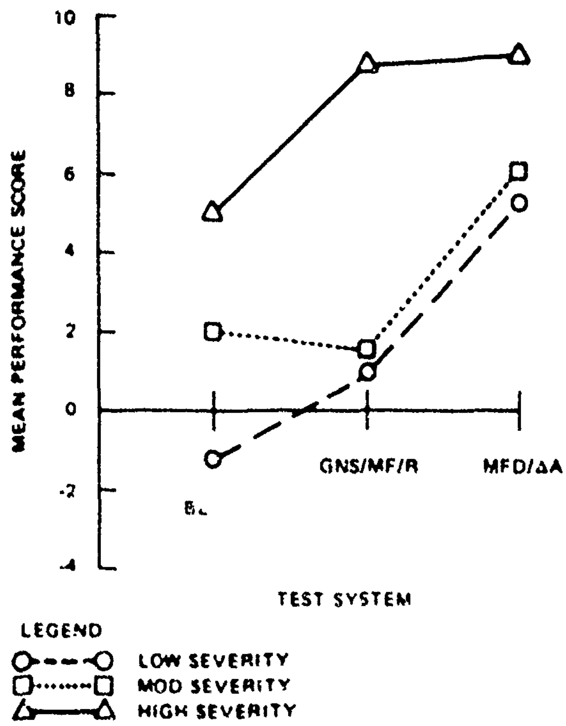


FIGURE 23 CONTRAST IN PERFORMANCE FOR EACH LEVEL WIND-SHEAR SEVERITY — NON-PRECISION APPROACH

In Figure 24, mean performance scores are compared across the test systems to show the effects of individual wind-shear profiles. It is apparent that profiles 8 and 4 were particularly difficult for the BL system, and that no improvement over BL is shown for high-severity profiles 5 and 10. As indicated in Figure 23, the MFD/ΔA performed substantially better than BL on low and moderate shears. Most of the improvement using this test system on high-severity shears occurred on profile 4.

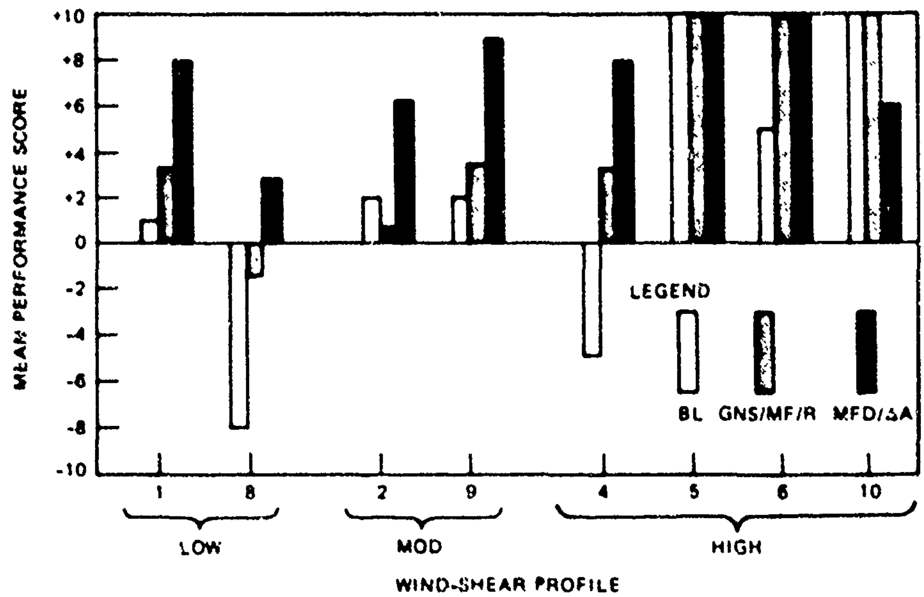


FIGURE 24 CONTRAST IN PERFORMANCE FOR INDIVIDUAL WIND-SHEAR PROFILES — NON-PRECISION APPROACH

The Friedman test[8] shows a probability of .02 that the differences in performance scores, examined across subject pilots, were independent of the test system used. A subsequent test (Wilcoxon) of the differences in performance between BL and the MFD/ΔA system was statistically significant at less than the .01 probability level.

2. Analysis

The following analysis of airspeed management, flight path control, and go-around performance will parallel the analysis given in Section IV-D for the precision approach. For the non-precision approach, however, direct comparisons between baseline and test system performance will not be meaningful in some instances because of the differences in approach management procedure. The principal differences arise from the use of the synthetic glide path (see Section V-A) for the test systems, which produces a vertical flight profile that is more like the precision approach than the standard, step-down non-precision approach procedure.

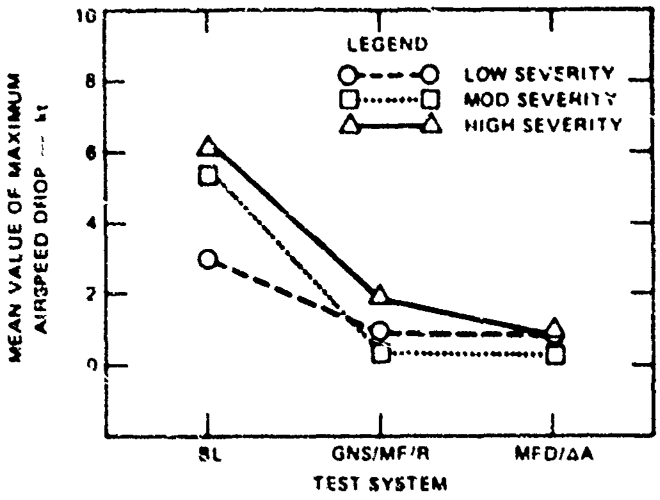
a. Airspeed Management

Summary data plotted in Figure 25 show that the ground speed management technique was used effectively to control for airspeed loss. The data points in Figure 25(a) are the maximum drop in airspeed below V_{APP} for the 500- to 100-foot approach segment, averaged across pilots for the three shear severity levels, and show the expected reduction in airspeed loss when the test systems were used. The corresponding plot given in Figure 25(b) for ground speed drop shows that the technique was used correctly--i.e., pilots were able to hold ground speed at or above the reference value.

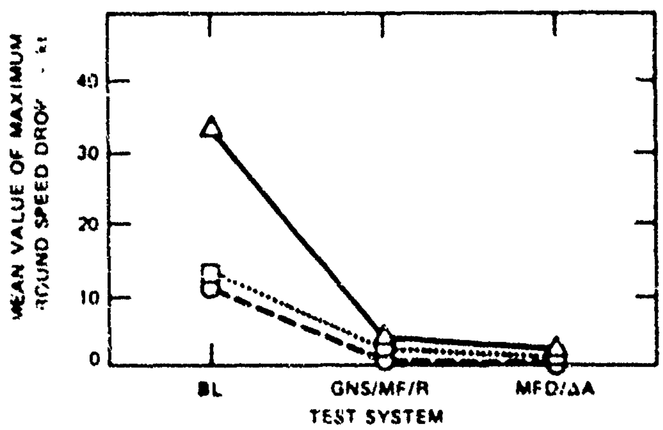
Figure 26(a) shows that airspeed error during the shear encounters was held to about 8 knots under baseline conditions and that speed pads as high as 22 knots, on a one-sigma basis, were recorded for high-severity shears when the test systems were used. The variability in airspeed error is indicated by the vertical lines extending above and below the highest and lowest data points to represent one standard deviation from the plotted values. Corresponding data on touchdown positions are given in Figure 26(b) and show no tendency toward long landings when the airspeed pad is used. The greater dispersion in touchdown position shown for the BL condition (vertical lines) is probably attributable more to variability in glide path control on the final approach segment than to differences in airspeed management technique. One-sigma deviations in touchdown position recorded for the test systems on high-severity shears were about 750 feet.

b. Flight Path Control

Data plots in Figure 27(a) indicate that glide path tracking accuracy using the synthetic glide path technique was comparable to that achieved on the precision approach using the ILS glide slope (see Figure 18 for comparison). The data points reflect glide path displacements over the 500- to 100-foot approach segment where most of the

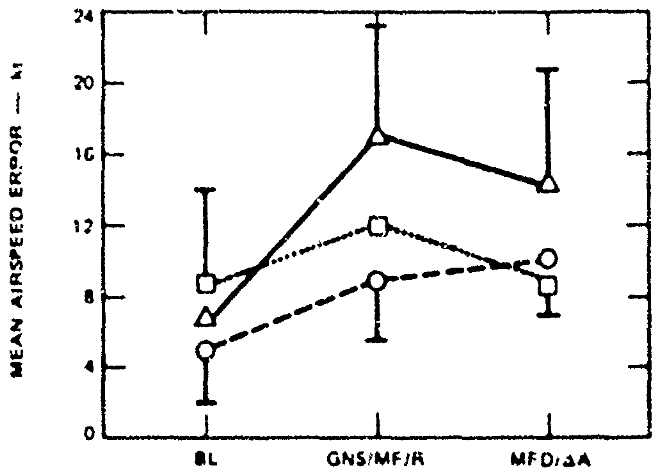


(a) MAXIMUM DROP IN AIRSPEED OVER THE 500-TO-100-FOOT NON-PRECISION APPROACH SEGMENT

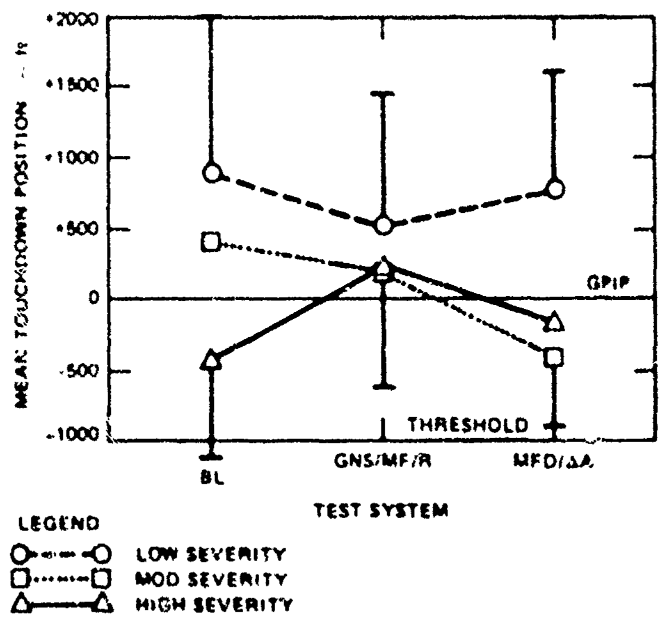


(b) MAXIMUM DROP IN GROUND SPEED OVER THE 500-TO-100-FOOT NON-PRECISION APPROACH SEGMENT

FIGURE 25 CONTRAST IN AIRSPEED MANAGEMENT FOR EACH LEVEL OF SHEAR SEVERITY — NON-PRECISION APPROACH

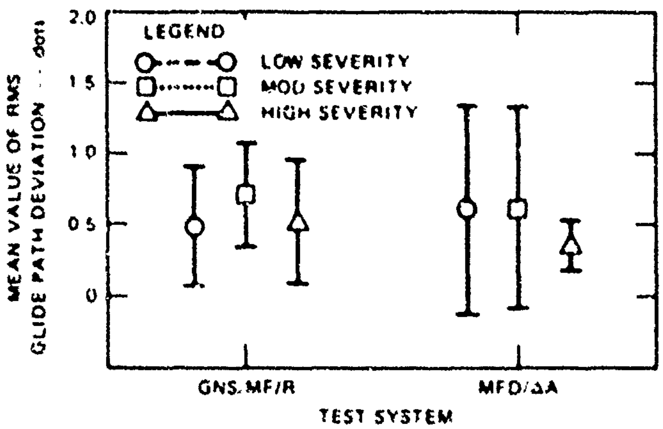


(a) MAGNITUDE AND VARIABILITY IN RMS AIRSPEED ERROR OVER THE 500-TO-100-FOOT APPROACH SEGMENT

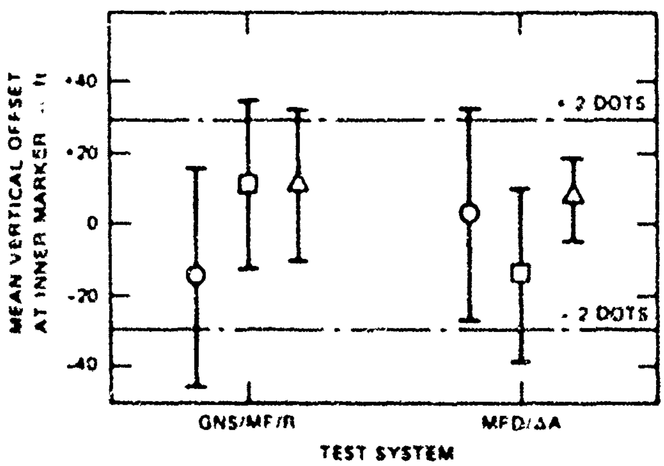


(b) AVERAGE TOUCHDOWN POSITION ALONG THE RUNWAY FOR EACH LEVEL OF SHEAR SEVERITY

FIGURE 26 CONTRAST IN AIRSPEED ERROR AND EFFECT ON TOUCHDOWN POSITION — NON-PRECISION APPROACH



(a) MAGNITUDE AND VARIABILITY IN RMS GLIDE PATH DISPLACEMENT OVER THE 900-TO-100-FOOT APPROACH SEGMENT



(b) MAGNITUDE AND VARIABILITY IN VERTICAL OFFSET AT THE INNER MARKER POSITION

FIGURE 27 ACCURACY OF GLIDE PATH TRACKING FOR THE SYNTHETIC GLIDE PATH TECHNIQUE wind-shear effect was encountered. As indicated, average rms displacements on the order of 1/2 dot were recorded, and variability across subject pilots (indicated by vertical lines above and below data points) was generally within one dot on a one-sigma basis. The substantial reduction in variability shown for the MFD/ΔA system on high-severity shears is attributable to the fact that go-arounds were executed on all of the severe shears except profile 5, a frontal shear condition with no turbulence and producing gradually increasing performance down to about 150 feet above the runway.

Figure 27(b) shows that tight glide path tracking generally produced approach outcomes that were within ±2 dot offset limits at the Inner Marker position (1860 feet from the GPIP in this simulation). The data also show that these limits were exceeded, on a one-sigma basis, in some instances.

c. Go-Around Performance

The acceleration margin computation (ΔA) was again used as the sole basis for displaying go-around advisories on the MFD/ΔA system (and as the principal basis on the CNS/MF/R system), and the performance of this technique is tabulated in Table 11 for each level of shear severity. In this tabulation, baseline data runs were omitted because recorded values of ΔA on the step-down baseline procedure are not commensurate with those obtained on the test system runs. The data show the same trend as those recorded on the precision approach.

With the exception of two runs on profile 4, and excluding the eight runs on profile 5 that always terminated with a within-limit touchdown, advisories were issued on all of the high-severity shear conditions. The nearly complete absence of advisories on the low-severity shears and on the moderate profile 9 again show that the ΔA system reliably distinguishes non-hazardous shear conditions and indicates a very low false-alarm rate. A high percentage of advisories is again shown for the profile 2, and in view of the poor landing outcomes recorded for this shear when it was attempted (50% outside limits), the advisory appears to be justified on this high-cross-wind-component condition.

Table 13

TABULATION OF GO-AROUND ADVISORIES BY WIND SHEAR PROFILE FOR DATA RUNS--NON-PRECISION APPROACH (N = 90)*

Wind Profile Number	Number of Runs	Number of Advisories	Percent of Runs
Low Severity			
1	19	1	5
8	17	0	0
Moderate Severity			
2	9	6	66
9	9	0	0
High Severity			
4	14	12	86
5	8	0	0
6	5	5	100
10	9	9	100

*50 Baseline runs not included; data missing on 10 GNS/MF/R runs.

The tabulation given in Table 14 shows the number of go-arounds actually attempted under each level of shear severity and the corresponding number of successful attempts. The percentages shown in parentheses relate these numbers to the total number of data runs for each test condition. The data show a reduction in the go-around rate on low-severity shears, relative to baseline, for both test systems, and a reduction in go-arounds on the moderate shear for the GNS/MF/R system. As expected, the go-around rate for high-severity shears increased when the MFD/SA system was used.

Table 14

TABULATION OF GO AROUNDS BY WIND-SHEAR SEVERITY
FOR EACH TEST SYSTEM--NON-PRECISION APPROACH

Test Condition	Number of Runs	Number of Go-Arounds	Number Successful
Baseline			
Low	20	11 (55%)	11 (100%)
Moderate	10	5 (50%)	5 (100%)
High	20	12 (60%)	9 (75%)
MFD/ΔA			
Low	20	5 (25%)	5 (100%)
Moderate	10	5 (50%)	5 (100%)
High	20	16 (80%)	15 (94%)
GNS/MF/R			
Low	16	7 (44%)	7 (100%)
Moderate	8	1 (12%)	1 (100%)
High	16	7 (44%)	7 (100%)

The increase in the percentage of successful go-arounds on high-severity shears is again considered to be the important result in this tabulation. Under baseline conditions, 25% of the go-around attempts resulted in ground contact (crashes), and this percentage was reduced to 6% for the MFD/ΔA system and to zero for the GNS/MF/R. This finding is consistent with the data shown in Table 10 for the precision approach.

3. Pilot Evaluations

After their sessions in the DC-10 simulator, the subject pilots were interviewed informally and were asked to answer questionnaires on their reactions to the test runs and their estimates of the acceptability of the various aiding concepts. The questionnaires are reproduced in Appendix F, showing the numbers of different answers given by the 10 pilots.

The key point is whether a system tested offered a solution to the wind-shear problem on non-precision approach and landing ("General," questions 1 and 2, Appendix F). The pilots judged the standard or BL system to be "no solution" or only a "basis for a potential solution." Their response for the primary system, MFD/ΔA, was 8 out of 10 for "basis" or "solution," significantly higher than for baseline. Also the alternate system, GNS/MF/R, was judged almost as good as MFD/ΔA.

On the subject of their experience with non-precision approach (NPA) operations ("Operations," questions 1-9), the pilots said that NPA is significantly more difficult than a precision approach; they made an average of 17.5 NPAs in the past year and all but one used the flight director. The three-step NPA maneuver [consisting of relatively steep descent from outer marker to minimum descent altitude (MDA), level out until runway is sighted, and final descent to landing by visual reference] is used normally by almost all. The final landing maneuver is the most difficult part according to half, while altitude control during the level part was most difficult for most of the others. If they had to make a go-around, 6 out of 10 thought that stick-shaker is the minimum safe speed ("Go-Around," question 1).

The quality of the DC-10 simulator was judged "good" to "very good," and the wind profiles were considered to be realistic ("General," questions 3 and 4).

The need for ground speed information and the usefulness of the ground speed/airspeed concept were endorsed by all hands. The major reservation, to quote one pilot, was "GNS/IAS speed concept is good, provided reported winds on ground are good." The dual-needle (V_{mo}) display of GNS and IAS was judged practical, and only one pilot found that it produced confusion. In the comparison of the dual-needle with the moving-tape display, the choice was about half and half ("General," question 6, and "Ground Speed," question 6) although only 4 out of 10 had previous experience with instruments of the vertical tape type.

All the pilots had used previously a flight director with a Fast/Slow command for thrust management, 6 out of 10 making it their primary speed control. This method of mechanizing the speed control function was endorsed almost unanimously.

The Collins MFD was preferred over BL by all hands; it was not found to call for any unsafe action, and was judged not "too active" by 9/10 of the pilots. To quote one pilot, "MFD is better for approach guidance, but rough on passengers." However, 9 out of 10 found it smooth enough for day-to-day airline operations. The synthetic glide path for NPA also drew high marks, being found valuable and significantly lowering workload ("Operations," question 10). The MFD with synthetic glide path helped make a more precise approach. On the question of when to use the MFD, 8 out of 10 recommended its use for all approaches, and 6 out of 10 recommended against the optional selection of MFD or baseline.

On executing a go-around maneuver, all the pilots found the flight director and the modified go-around steering commands to be helpful. The modified algorithm gave larger pitch commands than were comfortable, according to 4 out of 10, but seemed about right to the rest. Also, some half of the pilots endorsed the display of angle of attack during a go-around, but a significant number (4 out of 10) were uncertain about this information.

The acceleration-margin concept was heartily endorsed, all pilots agreeing that they would like to have the instrument in the cockpit and that the light gave a timely go-around warning. In using the instrument, most (7 out of 10) saw it only occasionally and used it to monitor the need for thrust.

Evaluation of the microprocessor-based alphanumeric display (RED) was not so favorable. A majority judged it to be helpful ("Operations," question 12, and "Run Evaluation Display," questions 5 and 6). All pilots had it monitored by the copilot rather than watching it themselves. The go-around advisory messages were judged to be the most useful of the RED functions by most (8/10) pilots. Comments by two pilots were enlightening: "RED was helpful, but I couldn't absorb/digest the intelligence in the time exposure," and "I was too busy with the new instruments to read the messages; also, I appreciated the wind information, but depended on the first officer to relay it to me." It was notable that all the pilots stated that they would prefer to be aided by "a black box" in making a go-around decision.

VI TAKEOFF STUDY

A. Situation Simulated

The simulation scenario adopted for the takeoff study was designed to represent a normal, full-thrust takeoff with reference speeds based on an aircraft gross weight of 375,000 lb and a 22° flap setting. Air density and temperature conditions represented in the simulation were set for a sea level field elevation and a standard day. The runway was 150 by 10,400 feet and there were no visibility restrictions.

Five wind profiles were developed especially for the takeoff tests and are identified in Appendix A as profiles 11 through 15. The first four profiles are thunderstorm wind fields characterized by a substantial headwind shearout during the first 500 feet of the climbout. On three of these thunderstorm shears (profiles 11, 13, and 14), the headwind shearout is accompanied by a downdraft in excess of 10 knots. The fifth wind profile (No. 15) represents a frontal shear, with a milder headwind shearout occurring in combination with a downdraft of less than 5 knots.

Takeoff sequences were initiated from brake release with the aircraft on the runway centerline. The subject pilot advanced the throttles to takeoff position where they were trimmed for a 102% N_1 setting by the "First Officer" (FO) in the right seat. The FO called out V_1 (130 knots) and V_R (136 knots), and the pilot executed a normal rotation and climbout following the test procedure to be described in Section VI-C, below.

B. Systems Tested

All takeoff sequences were flown using the instrument panel configuration shown in Figure 10 for the MFD/AA test system. However, the only element of this test system considered appropriate to the takeoff situation is the modified flight director pitch steering commands developed for go-around guidance (see description in Section III). The standard DC-10 pitch steering command for takeoff, which attempts to stabilize the climbout at V_2 + 10 (158 knots) and incorporates a minimum angle-of-attack reference, was used as a baseline comparison system.

To obtain additional information on possible control strategies for coping with the shear encounter on takeoff, two variations on the use of the modified flight director and two variations of the baseline procedure were tested. The four resulting test situations were defined as follows:

(1) Follow standard DC-10 pitch steering command immediately after rotation; this is BL;

(2) Pitch up to 15° at rotation and thereafter attempt to establish and maintain V_2 + 10 by reference to the airspeed indicator, with no pitch steering command available; hereafter referred to as "no flight director" (NOFD);

(3) Follow the modified pitch steering command immediately after rotation; hereafter referred to as "MPD at lift-off" (MPD);

(4) Use BL procedure for rotation and initial climb and switch to MPD when shear effects are encountered; hereafter referred to as "MPD option" (MPD opt).

C. Evaluation Plan

The basic intent of the takeoff study was to obtain additional data on the effects of the low-level shear encounter during the takeoff sequence and to conduct an informal evaluation of the differences, if any, in adopting the four climbout control strategies just described. Accordingly, no formal experimental design was developed and no special scoring scheme for takeoff outcomes was defined.

The "subject pilots" for this exercise were the two Bunker-Ramo project pilots and an FAA pilot. These three pilots have had extensive experience with the FAA wind-shear program, have participated in earlier simulation studies, and were thoroughly familiar with the wind-shear conditions. Each of these three pilots flew four 5-run test series, one for each of the alternative climbout control strategies. The evaluation of takeoff outcomes was thus based on a total of 60 data runs, and contrasts between alternative control strategies were based on 15 runs using each technique.

Each session consisted of a brief training series on the selected control technique and then one data run for each of the five wind profiles. On BL and NOFD runs, the pilots made their best effort to get through the shear without excessive altitude loss or crashing. When either version of the MPD technique was used, the pilots attempted to follow the steering commands as closely as possible so that an evaluation of the effectiveness of the flight director could be obtained. In all instances, takeoff power was initially set at 102% of N_1, and when severe shear effects were encountered the throttles were advanced to an overboost condition of 113% of N_1.

D. <u>Results</u>

The outcomes of the takeoff attempts through the five test shear conditions were remarkably consistent for the three pilots and, for the most part, showed little difference across the four control strategies. Typical responses to the different shear conditions are illustrated in Figures 28 and 29. The traces shown in Figure 28 for each wind profile are strip-chart recordings obtained for the baseline procedure. Those in Figure 29 are for a different pilot using the MPD at lift-off.

These traces show that encounters with the combined headwind shear-out and low-level downdraft (profiles 13 and 14) were extremely hazardous for both BL and the test system. Crashes were recorded on all of the test runs under these conditions. On profile 11, the severest portion of the downdraft is encountered above 500 feet and, terrain permitting, this shear might be survivable. Note, however, that a 500-foot loss of altitude is typical for this shear condition, and the location of the shear encounter relative to terrain features in the airport surroundings would be a critical factor. Encounters with the milder thunderstorm profile with no downdraft (profile 12) and with the frontal shear (profile 15) were comparatively benign; none of the pilots had any difficulty climbing through these conditions using any of the four control strategies.

A more complete assessment of the outcomes of these shear encounters for each of the alternative control strategies is given in Table 15.

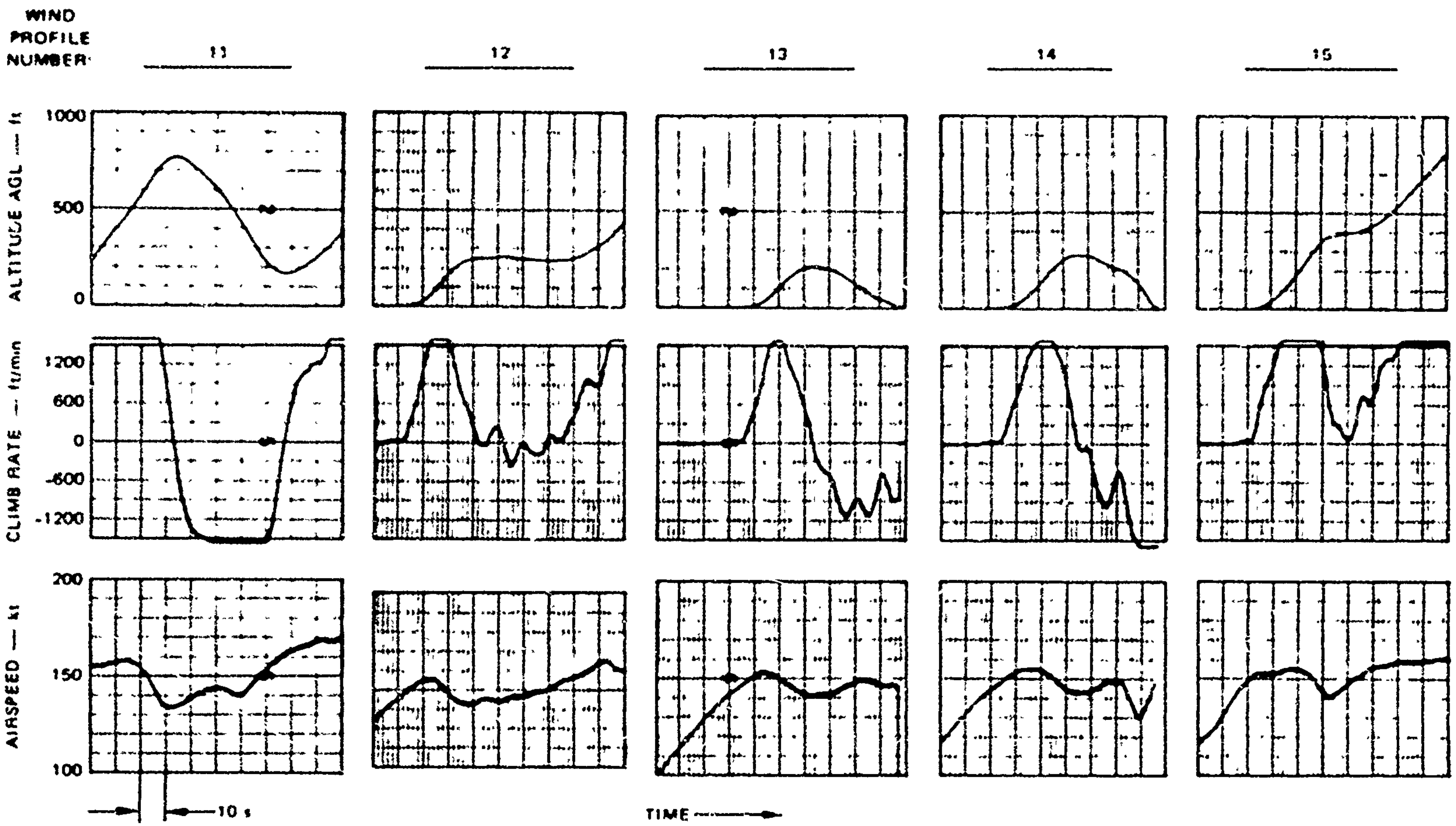


FIGURE 28 TYPICAL SYSTEM RESPONSE TO WIND-SHEAR ENCOUNTERS ON TAKEOFF — THE BASELINE SYSTEM

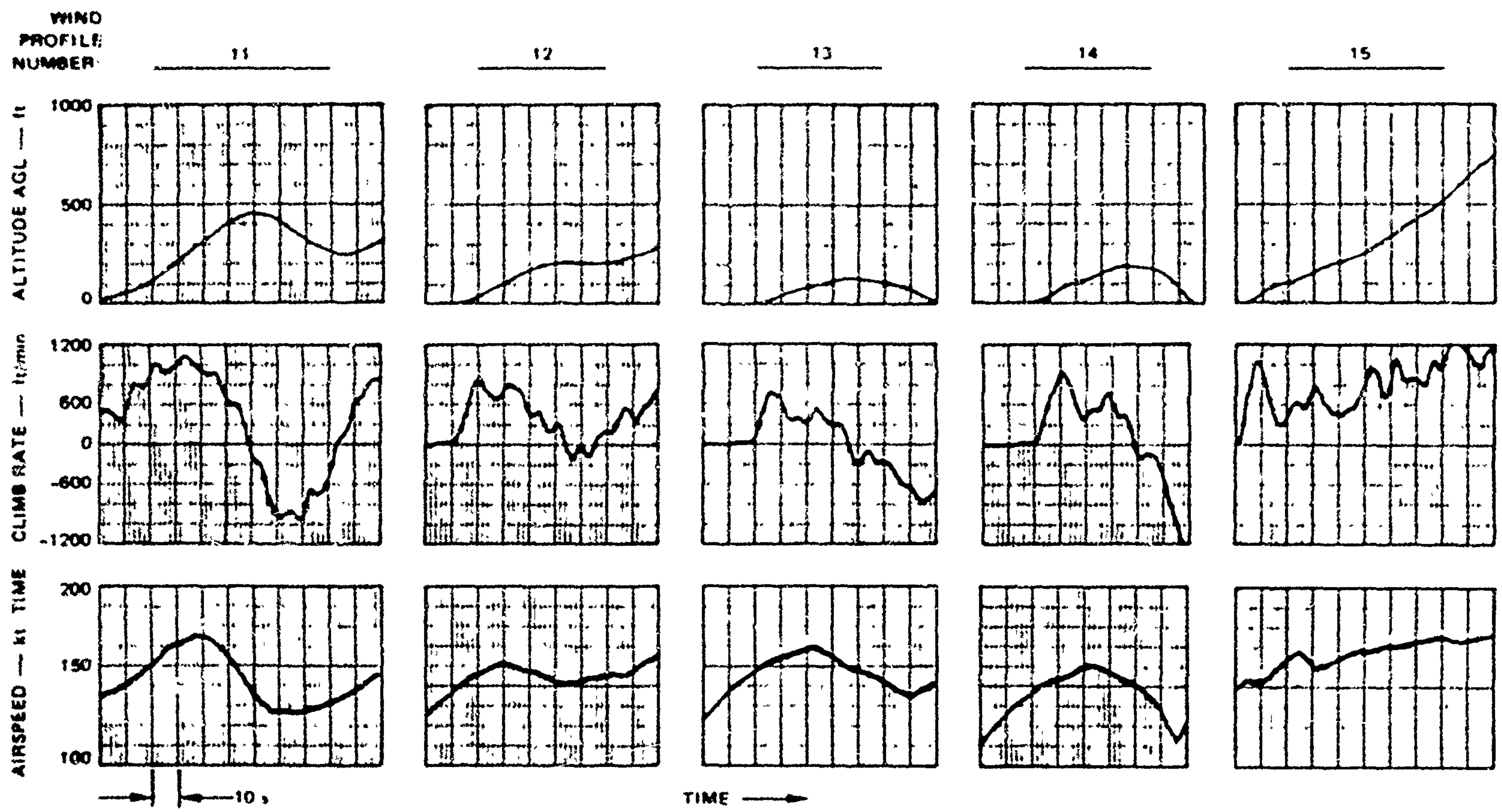


FIGURE 29 TYPICAL SYSTEM RESPONSE TO WIND-SHEAR ENCOUNTERS ON TAKEOFF — THE MFD SYSTEM

Table 15

TABULATION OF TAKEOFF OUTCOMES FOR EACH TEST SYSTEM AND CONTROL STRATEGY

Takeoff Outcome by Wind Profile \ Control Strategy	BL	NOFD	MPD	MPD opt
Number of crashes				
WP 11	1	0	0	0
WP 12	0	0	0	0
WP 13	3	2	3	3
WP 14	3	2	3	3
WP 15	0	0	0	0
Total	7	4	6	6
Mean Airspeed Loss (kt)				
WP 11	22	30	35	31
WP 12	13	14	13	12
WP 13	12	21	24	15
WP 14	14	24	39	25
WP 15	14	11	9	13
Mean Altitude Loss (ft)				
WP 11	477	530	213	553
WP 12	20	20	20	27
WP 13	230	233	287	220
WP 14	290	290	233	280
WP 15	0	0	0	13
Mean Recovery Altitude (ft)				
WP 11	165	210	233	160
WP 12	240	250	193	223
WP 13	0	60	0	0
WP 14	0	0	0	0
WP 15	*	*	*	*

*Under these test conditions, climbout was accomplished with no significant loss of altitude, so "recovery altitude" is not applicable.

Summary data on takeoff outcomes are provided for four key flight situation parameters for each combination of wind-shear and control technique. The "number of crashes" is self explanatory. Mean values of airspeed loss, altitude loss, and recovery altitude are based on three runs for each test condition--i.e., they are averaged across pilots.

The data indicate that crashes occurred on approximately one-third of the takeoff attempts (6 or 7 out of 20) for all test systems and control strategies except the "no flight director" (NOFD) condition. On the NOFD runs, no flight director pitch steering was available and the pilots attempted to trade airspeed for climb performance, down to stick shaker, when the shear was encountered. This technique saved one of the three takeoff attempts against both of the most hazardous shears (13 and 14), and thus reduced the overall crash rate to 20% (4 out of 20).

In general, airspeed and altitude loss during the shear encounters was about the same for the alternative control strategies for a given wind profile. On profile 11, the average altitude loss using the MPD at lift-off was substantially less than for the other three techniques. A slight trend toward better performance for the MPD is also shown for the more difficult profile 14, but the differences were not enough to reduce the relative number of crashes the overall picture given by the takeoff outcome data, then, is that individual wind-shear effects were dominant and that none of the aiding techniques tested could cope effectively with the combined effects of a headwind shearout and downdraft during the first 500 feet of the climbout.

VII CONCLUSIONS AND RECOMMENDATIONS

In this section, the major findings of the study are summarized and related to the objectives of the test program. Since the primary concern of the study was to demonstrate the potential operational performance of the MFD/ΔA system, the presentation of conclusions emphasizes the performance of that system and its component systems and features. For a more complete presentation and discussion of the data supporting this summary of test results, the reader is referred to the preceding sections of the report.

Following the presentation of conclusions is a discussion of recommendations relating to the interpretation of test results, the need for additional development of airborne systems, and requirements for further development of test procedures for qualifying airborne wind-shear management systems.

A. Conclusions

1. MFD/ΔA System Performance

Approach outcome data for both the precision and non-precision approach demonstrate a substantial and operationally significant increase in the safe management of low-level shear encounters when the pilot-aiding features of the MFD/ΔA system are available. This system produced within-limit touchdowns or successfully executed go-arounds on all of the more hazardous high-severity shear encounters for the precision approach; on the non-precision approach this level of performance was achieved on all but one of the high-severity shear encounters. In contrast, unsafe approach outcomes were recorded for 40% of the high-severity shear encounters (8 out of 20) under baseline conditions for the precision approach, and for 30% of the non-precision approaches (6 out of 20) when baseline procedures were used.

Although approach outcomes on the low- and moderate-severity shears were substantially better than baseline when the MFD/ΔA system was used, the overall level of performance on these less-hazardous shear encounters did not completely satisfy our criteria. Out-of-limit approach outcomes were recorded on 17% of the precision approaches (5 out of 30) for low and moderate shear conditions. However, an out-of-limit result was recorded on only one of the 30 non-precision approaches for these shear conditions. The comparative drop in overall MFD/ΔA system performance on the low and moderate shears was due primarily to the go-arounds recorded for these conditions. These go-arounds were successful, and operational safety was not impaired. However, they were construed as demonstrating less-than-perfect performance of the go-around advisory feature of the test system.

2. Role of Go-Around Advisories and Improved Climbout Guidance

The go-around advisories based on acceleration margin, and the modified pitch steering provided for go-around guidance, are considered to be the principal basis for the marked improvement in the safe management of high-severity shear encounters that was demonstrated in this study. Both the MFD/ΔA and the GNS/RED systems generated timely go-around advisories on the most severe shears (profiles 4, 6, and 10) for all of the precision approaches (and for all but two of the non-precision approaches) and successful go-arounds were accomplished in every case. On the less severe profile 5, no advisories were generated, and within-limit landings were recorded for all of the encounters with this shear. This finding contrasts sharply with the 57% success rate (8 out of 14) for go-around attempts against the same shear conditions using the baseline system.

With some exceptions, the go-around advisory system reliably distinguished the less hazardous low and moderately severe shears. However, in the precision approach study advisories were generated on 17% of the encounters with profile 1 (classified as "low" severity) and on 85% of the encounters with profile 2 (classified as "moderate" severity). These findings could be construed as representing a substantial "false" or "nuisance" alarm rate. However, the subject pilots were nearly unanimous in rejecting the approaches attempted under profile 2 conditions, due to the excessive cross-wind that persisted to a very low altitude. Profile 1 can be negotiated but has high shear rates at low altitude. We would therefore conclude that the advisory system performed appropriately on profile 2 and that a warning would be advisable on profile 1.

3. Performance of the Synthetic Glide Path

Approach outcomes on the non-precision approach, when the Collins-developed synthetic glide path technique was used, showed the same high level of performance as that recorded on the precision approach using ILS guidance and the modified flight director. An even greater improvement over baseline system performance was recorded on low- and moderate-severity shears. On the overall assessment of approach outcomes, the MFD/ΔA system performance was very close to the highest expected score. We concluded that the synthetic glide path technique, used in conjunction with the go-around guidance feature, was a critical factor in demonstrating improved performance on the non-precision approach.

4. Pilot Aiding on Takeoff

The results of the takeoff study indicate that neither the standard flight director nor the modified pitch steering commands were effective for coping with the more severe shear encounters occurring in the first 500 feet of the climbout. On shear encounters characterized by the combined effects of a headwind loss and a downdraft in this altitude range, none of the takeoff attempts were successful when any form of pitch steering command was followed. A slight increase in the pilot's ability to manage this type of shear encounter was recorded when pitch steering commands were not used and the pilot nursed the aircraft through the shear, trading off airspeed down to stick shaker speeds to avoid ground contact. We conclude that none of the takeoff control strategies tested contribute in any substantial way to the low-level wind-shear problems for takeoff operations.

5. Pilot Evaluations

Subject pilot critiques of the test systems indicated a very high positive acceptance of the aiding features tested and a positive assessment of their effectiveness and practical value for managing the low-level shear encounter. Most of the pilots felt that the MFD/ΔA system represented a sound "solution" for the wind-shear problem or that it had excellent potential. As in previous studies, the ground speed management and modified flight director steering were very highly regarded, and their implementation in the airline cockpit for routine use was endorsed by all of the pilots.

The general assessment of the go-around system was also positive, in that all of the pilots accepted the advisories as valid, at least most of the time, and they were unanimous in their acceptance of some form of flight director assistance for the go-around maneuver. The advisory light was judged to be more acceptable than the alphanumeric readout (RED), although more than half of the pilots liked the additional information available in the RED display concept. As anticipated, pilot reactions to the moving tape display were mixed, with less than half of them indicating a preference for this type of presentation.

B. Recommendations on Instrumentation

The aiding systems that showed a significant performance improvement over baseline in wind shear required instrumentation of certain aircraft variables and wind components that are not available in many current aircraft. Certain other required quantities that are available in some aircraft but not in others are not measured currently to the necessary accuracy or with the required response time. Wind shear is a dynamic phenomenon, so the smoothing (or averaging) time of an instrument must be chosen carefully to respond quickly enough without being so fast that it is overexcited by turbulence. Of the quantities that are usually not available or not measured adequately, the most important are discussed in the following paragraphs.

1. Ground Speed

Speed over the ground, or (approximately the same) slant range rate to the glide path intercept point on the runway, is a missing state variable in many approaches and is needed for determination of longitudinal wind at the airplane. As George J. Moussally has shown[10], the significant factors in ground speed measurement for coping with wind shear are update time, accuracy, bias error, and smoothing time. It was assumed here that the measurement will be made on-board the airplane so there will be no transmission delay. Figure 30 shows the relationship

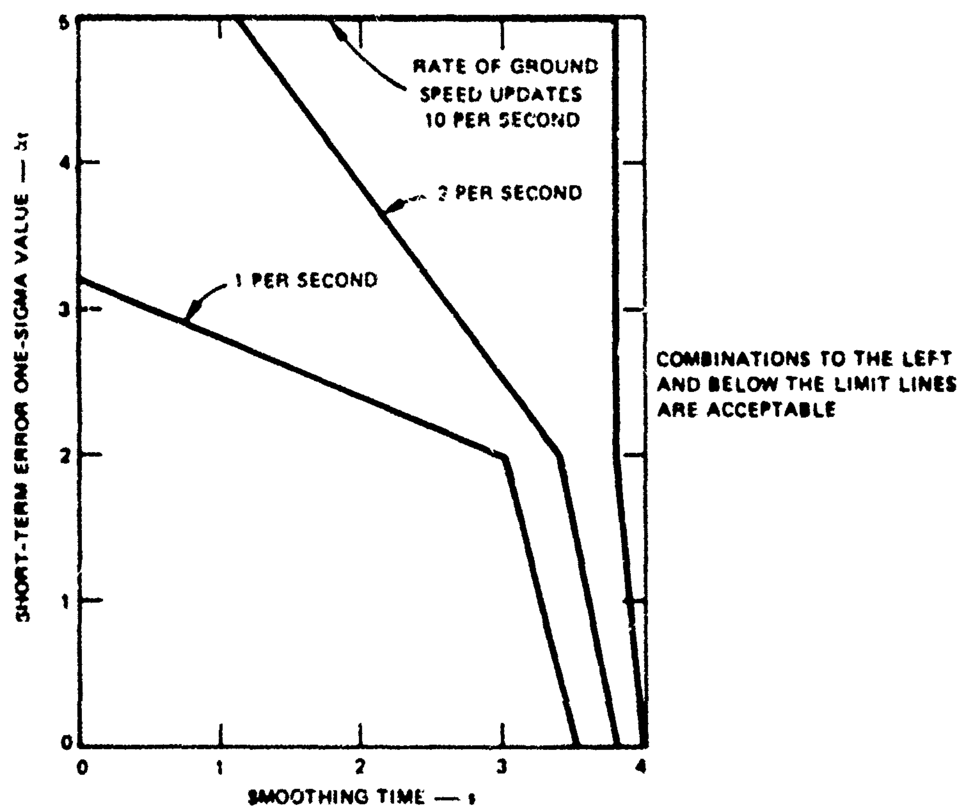


FIGURE 30 SPECIFICATION LIMITS FOR GROUND SPEED MEASUREMENT

between the acceptable values of rms random error, smoothing time, and update rate. Moussally also found that a bias error within the ±5 knot limits would be acceptable.

On other programs the FAA is conducting research and development projects on cost-effective techniques for airborne measurement of ground-speed that will meet the above specifications. We recommend that these projects be continued to a successful conclusion and a demonstration of commercial feasibility. We also recommend that instrumentation of ground speed to the above specifications be made a requirement in any system for coping with low-level wind shear.

2. Altitude and Altitude Rate

Reasonably accurate and responsive measurement of altitude above the runway level is a requirement; in many cases, altitude above the terrain under the approach path will do as well. The accuracy required will of course depend on the visibility; in a visual-meteorological-conditions non-precision approach to a 350-foot ceiling and 5000-foot runway visual range (RVR), an rms error of 13 feet or less has been found acceptable (App. B).

In the same way, an altitude rate measurement of good quality is required for tight path-following and for timely response to changes in vertical winds. Acceptable smoothing times have been found to be about 1.0 s (App. B). This is much lower than the smoothing times of many vertical rate instruments in current use, and in fact is comparable to that of a modern instantaneous vertical indicator (IVSI). We recommend that altitude and altitude rate measurements meeting these specifications be required in any aiding system.

3. Runway Winds

The tests reported here support a firm requirement for accurate knowledge of the winds on the runway; the along-runway component is needed by algorithms such as the acceleration margin and the airspeed/

ground-speed technique, and the cross-wind component is needed to enable the pilot to anticipate his lateral control action. On approach and landing the wind readings are needed in the touchdown zone; on takeoff they should be read at both the near and far ends of the runway. Because the winds can change rapidly in wind-shear situations such as thunderstorms, the data should be transmitted to the pilot with as little delay as possible,[9] certainly no greater than 1.5 minutes.

Measurement of winds at points on the runway is made difficult by the occurrence of wake gusts from aircraft landing or taking off. On other projects the FAA is developing and deploying at many airports an array of ground-level wind sensors that will measure the winds at several points of the airport territory. It seems likely that winds at the desired points on a runway can be estimated with sufficient accuracy by interpolating the readings of the multiple sensors. We recommend that the FAA include an investigation of this technique in its R&D program.

C. Recommendations on Aiding Systems

The MFD/ΔA system performed well enough to be recommended as a solution to the wind-shear problem on approach and landing. We do not mean to imply, of course, that MFD/ΔA is the only solution nor even that it is the most economical solution. We can only say that it is the system that has been found to work, and that the line of development we took (starting with minimal changes to the DC-10 instrumentation and introducing more complexity only when needed for improved performance) implies that it should be reasonably cost effective.

Note that the MFD/ΔA system consists of four functional elements: a programmed speed pad when anticipating a head-wind loss (provided by the Fast/Slow algorithm and thrust control procedure based on ground speed), tight path control (provided by the modified flight director steering), a go-around decision aid (provided by the acceleration margin computation), and a minimum-height-loss guidance aid for go-around (provided by the modified go-around steering command on the flight director). Even with all the simulator tests and analytical work that have been done, it is not easy to assess the relative merit of the individual functional elements. However, we have tested[3] the speed control and MFD without the go-around aids and have found the performance, while better than baseline, not to be adequate. Therefore we recommend that any aiding system for wind shear include an effective form of go-around aid.

Perhaps the most important thing to come out of the series of wind-shear tests and experiments is the design of a practical and effective experimental procedure for testing proposed aiding systems for approach and landing. The procedure is that used in the precision approach and non-precision approach tests reported here, and includes the following ingredients:

- A collection of realistic three-dimensional wind models of three levels of severity. The wind field includes both shear and turbulence (when appropriate), and is programmed as functions of altitude and displacement.
- An airplane simulator of good quality with a good visual scene generator. In these turbulent and dyanmic wind conditions, simulator motion is needed for fidelity and for providing the pilot realistic cues. The airplane simulated is close to the upper limit of the normal range of landing weight.
- Participation of some 8 to 10 subject pilots, preferably with experience in airline operations; the test results are averaged across the pilots to compensate for different proficiencies.
- Presentation of wind profiles and aiding systems to the subject pilots is counterbalanced and randomized to compensate for learning and fatigue.
- The training or familiarization runs include some wind profiles with shear, but do not include the test profiles.
- A performance scoring method like that described in Appendix D is adopted.

We recommend that a test of this type be prescribed for the qualification of any candidate aiding system. The MFD/ΔA has, of course, passed the test. To be considered successful, a candidate system should be required to show both a significant improvement (for example, a mean score difference of at least 4.5 using Appendix D) over conventional or baseline approach management, and an adequate absolute level of performance (for instance, a mean score of 6.0 or more).

D. Recommendations on Takeoffs

The tests show that there are realistic wind-shear conditions that, occurring on takeoff, exceed the aerodynamic and thrust capability of the airplane. An attempt to make a normal takeoff in such a situation cannot be retrieved by pilot action. The most appropriate recourses we have found are to not attempt to take off at all, to take off in a different direction, or to prolong the takeoff roll so that rotation will lift the airplane off with 20 knots or more of excess airspeed. Either action, in practice, requires advance notice (that is, prior to starting the takeoff roll) of the wind-shear condition and location.

Such advance notice is not easy to provide; if required to be based on exact measurements, the instrumentation may well be prohibitively expensive. However, there is a possibility that a useful warning could be developed by comparing the ground-level winds at the near end of the runway, the far end, and some farther point on an extension of the runway centerline. These data could perhaps be obtained by processing the readings of the wind-sensor arrays, mentioned above, that the FAA is installing at many airports. The information should be transmitted to the pilot with small delay, of course; 1.5 minutes would seem to be the maximum acceptable.[9] We recommend that the FAA continue examination of the problem presented by wind shear on takeoff, and that analysis of the feasibility of the warning based on ground-level wind data be included in the investigation.

Appendix A

DESCRIPTION OF WIND PROFILES

The first ten diagrams in this appendix show the mean wind components, as encountered on a 3° glide slope, for the approach wind profiles used in these tests. The takeoff wind profile wind components, as encountered on a 6° departure path, are shown in plots 11-15.

1. Mean Wind Specification

Each wind profile includes three wind components specified as a function of both altitude and distance along track. Each component is specified as a table lookup function with up to 21 altitude values and up to 16 distance values with straight-line interpolation between points. The altitude points are not equally spaced nor are they the same for each wind profile, although they are the same over all distance values of a given profile. The maximum amount of storage required for the mean wind values is $3 \times 21 \times 16 = 1008$ points.

2. Turbulence Specification

Turbulence parameters are included with each wind-shear profile. Six parameters (3 rms intensities and 3 scale lengths) are each specified as a function of altitude using a table lookup function with up to 21 altitude values. The maximum amount of storage required for the turbulence associated with a wind profile is $6 \times 21 = 126$ points. This brings the maximum total storage for a wind profile with turbulence to $1008 + 126 = 1134$ points.

The turbulence models used are developed from the Dryden spectra. Turbulence wind components are generated by feeding a random, white, zero mean, unit-variance input into a filter F(s). Transfer functions are as follows:

$$\text{Longitudinal} \qquad F_u(s) = \sigma_u \sqrt{\frac{L_u}{\pi V_a}} \frac{1}{1 + \frac{L_u}{V_a}s} \quad ;$$

$$\text{Lateral} \qquad F_v(s) = \sigma_v \sqrt{\frac{L_v}{2\pi V_a}} \frac{1 + \sqrt{3}\frac{L_v}{V_a}s}{\left(1 + \frac{L_v}{V_a}s\right)^2} \quad ;$$

$$\text{Vertical} \qquad F_w(s) = \sigma_w \sqrt{\frac{L_w}{2\pi V_a}} \frac{1 + \sqrt{3}\frac{L_w}{V_a}s}{\left(1 + \frac{L_w}{V_a}s\right)^2} \quad ;$$

where:

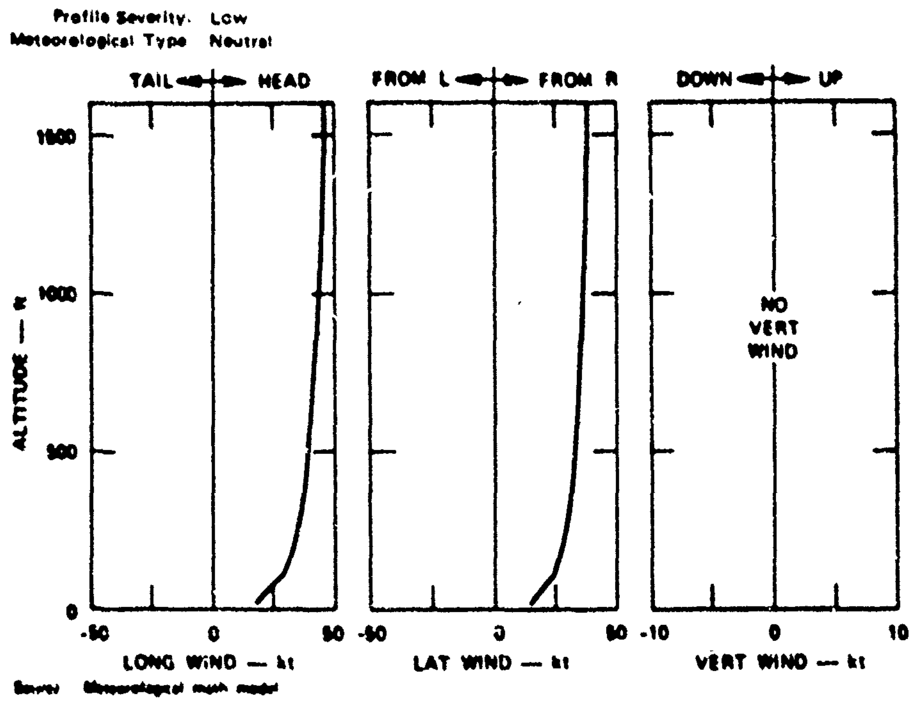
$\sigma_u, \sigma_v, \sigma_w$ = rms intensities

L_u, L_v, L_w = Scale lengths

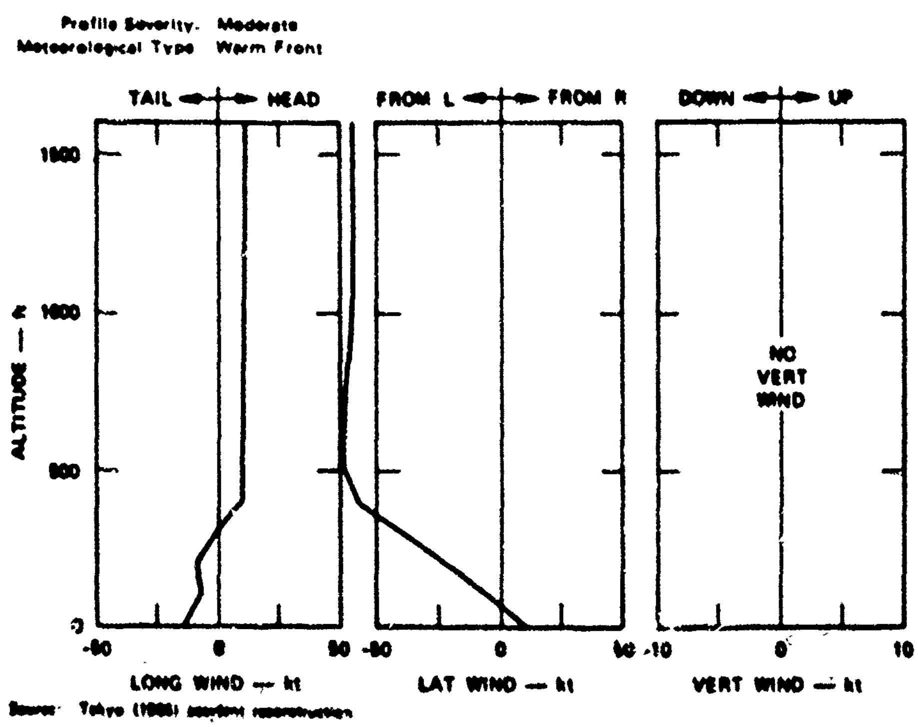
V_a = True airspeed

s = Laplace transform variable.

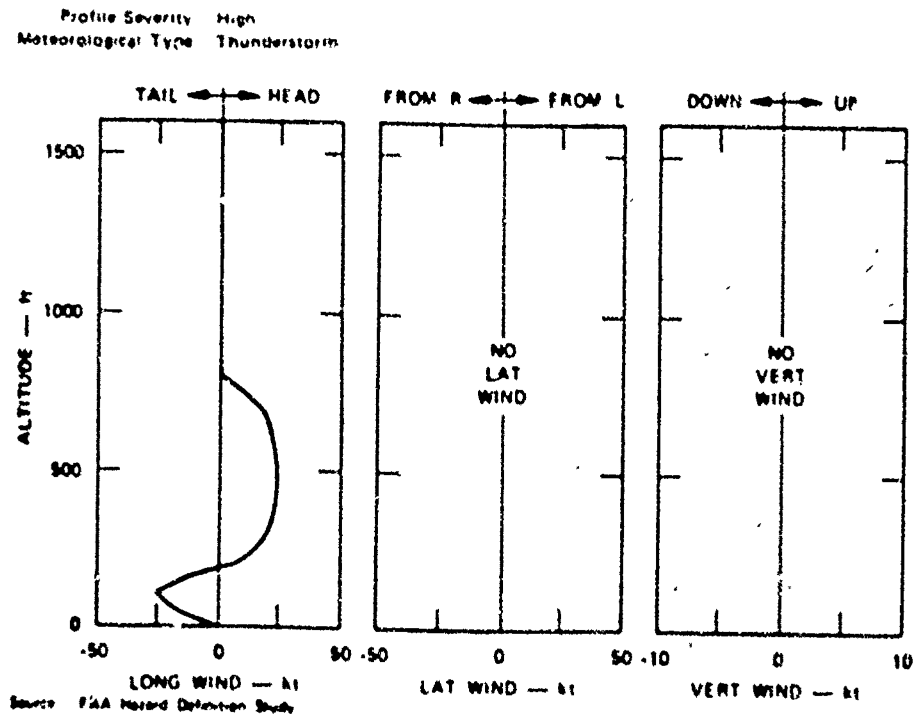
Basic sources and procedures used to develop these wind models have been reported[4].



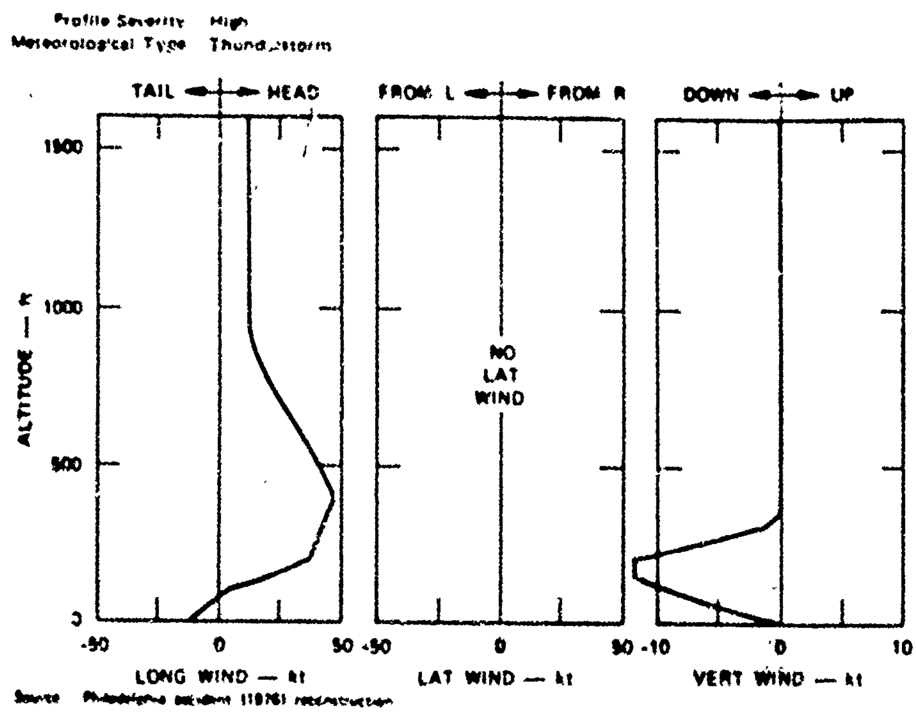
WIND PROFILE 1, APPROACH ON 3° GLIDE PATH



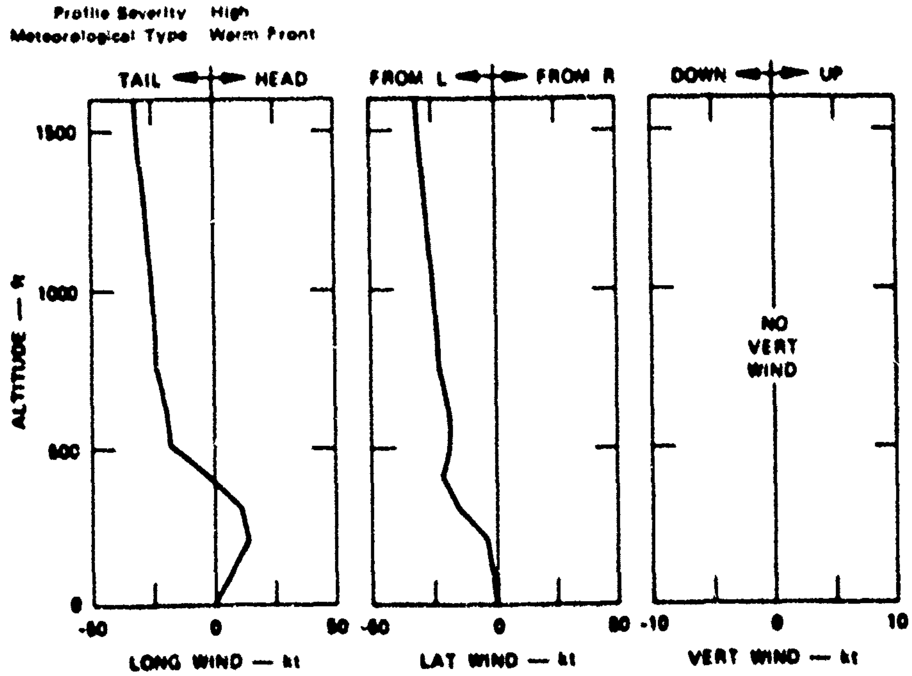
WIND PROFILE 2, APPROACH ON 3° GLIDE PATH



WIND PROFILE 3, APPROACH ON 3° GLIDE PATH

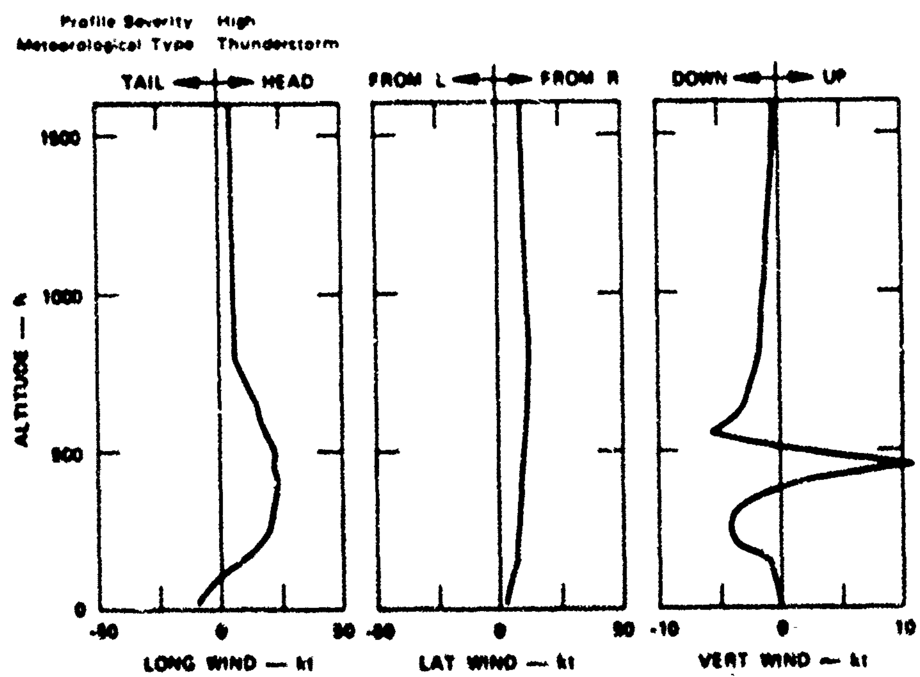


WIND PROFILE 4, APPROACH ON 3° GLIDE PATH



Source: Logan accident (1973) reconstruction

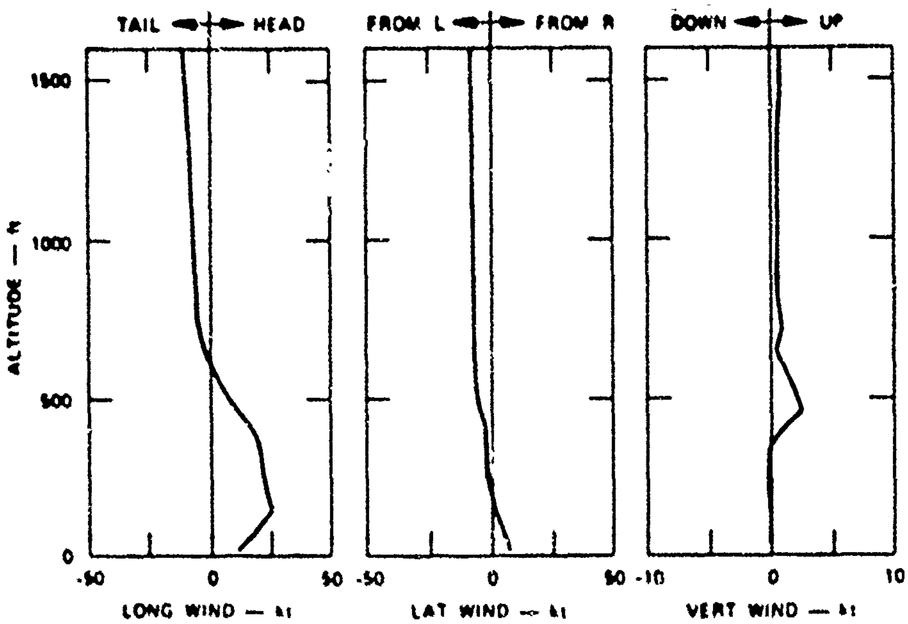
WIND PROFILE 5, APPROACH ON 3° GLIDE PATH



Source: Kennedy accident (1975) reconstruction

WIND PROFILE 6, APPROACH ON 3° GLIDE PATH

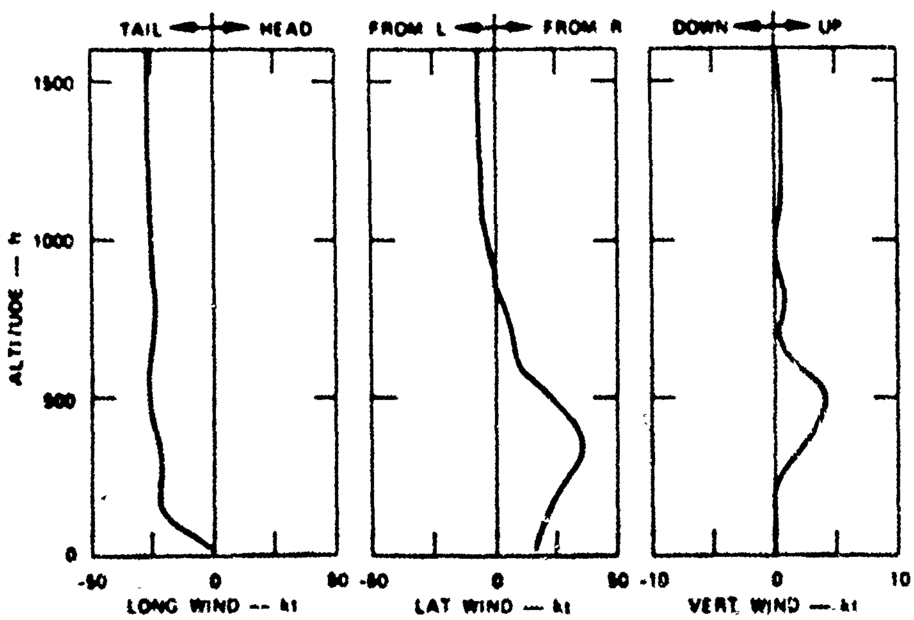
Profile Severity Moderate
Meteorological Type Thunderstorm



Source Tower measurements

WIND PROFILE 7, APPROACH ON 3° GLIDE PATH

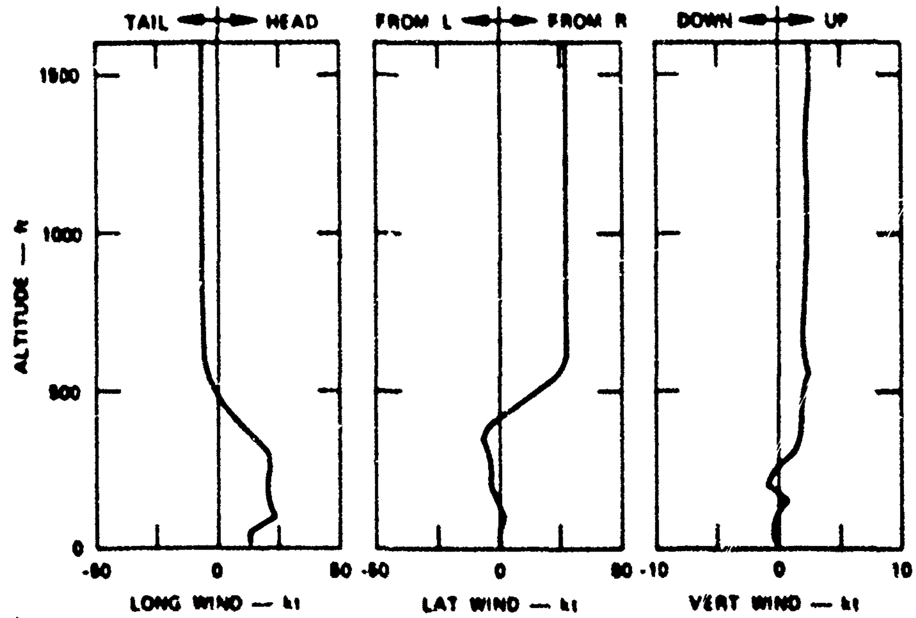
Profile Severity Low
Meteorological Type Thunderstorm



Source Tower measurements

WIND PROFILE 8, APPROACH ON 3° GLIDE PATH

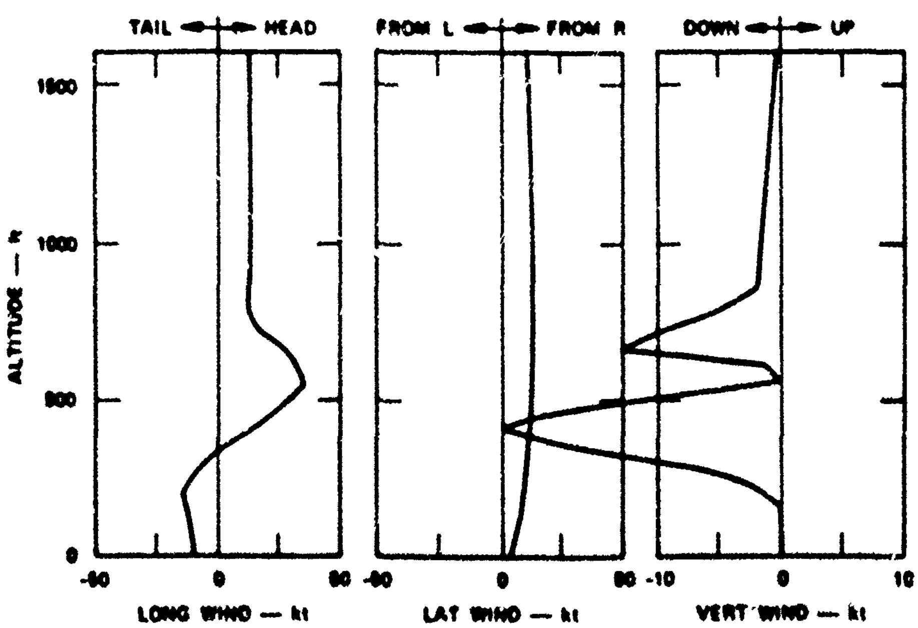
Profile Severity: Moderate
Meteorological Type: Cold Front



Source: Tower measurements

WIND PROFILE 9, APPROACH ON 3° GLIDE PATH

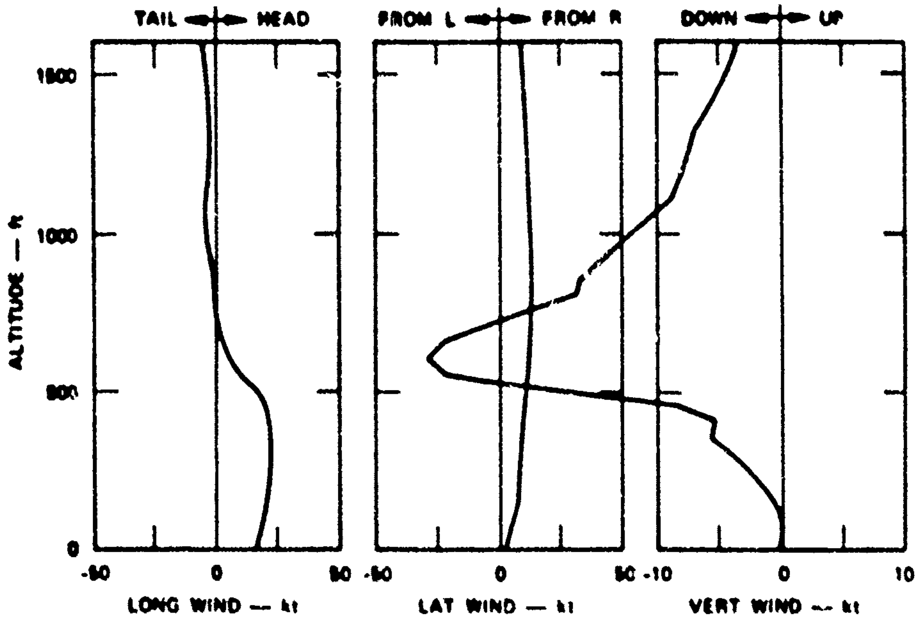
Profile Severity: High
Meteorological Type: Thunderstorm



Source: Kennedy accident (1975) reconstruction

WIND PROFILE 10, APPROACH ON 3° GLIDE PATH

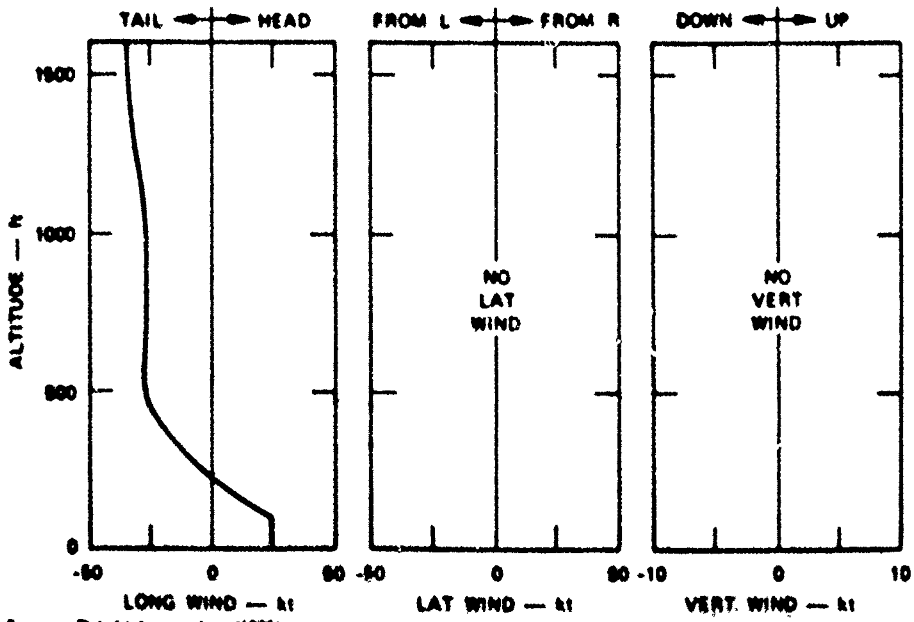
Meteorological Type: Thunderstorm



Source: Kennedy accident (1975) reconstruction

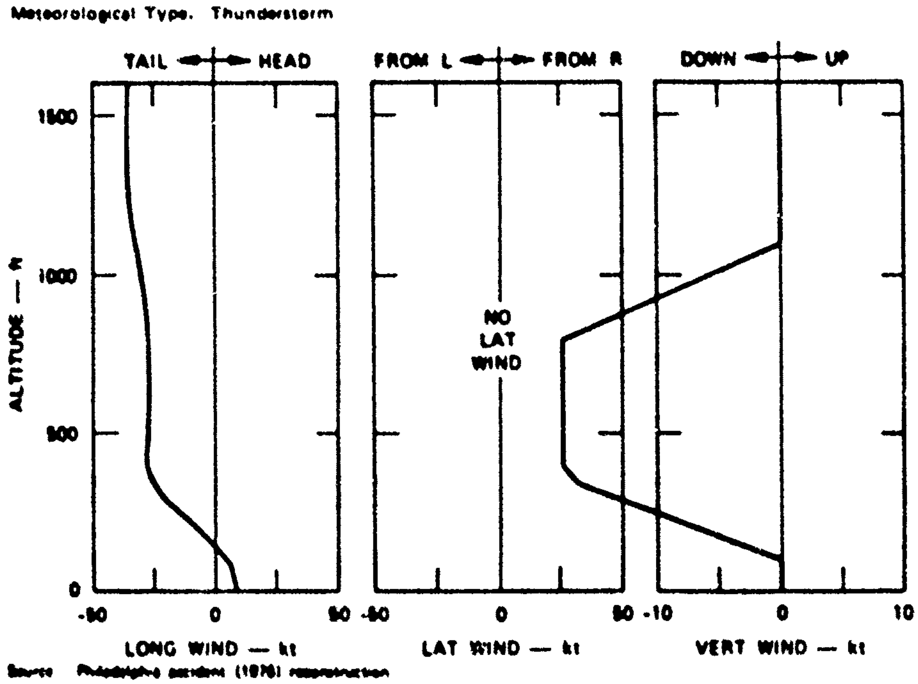
WIND PROFILE 11, TAKEOFF WITH 6° CLIMBOUT

Meteorological Type: Thunderstorm

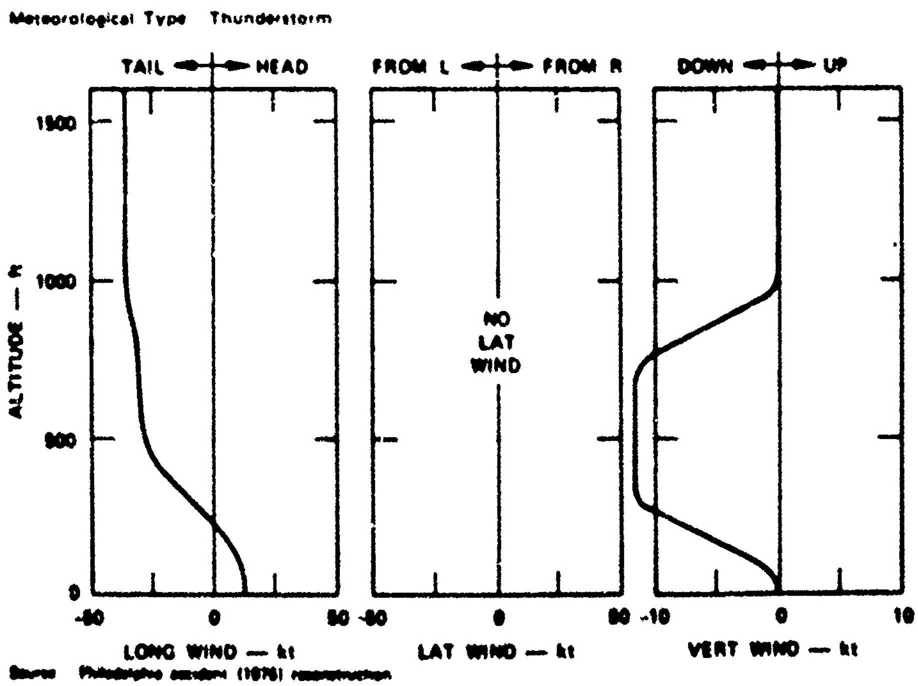


Source: Philadelphia accident (1976) reconstruction

WIND PROFILE 12, TAKEOFF WITH 6° CLIMBOUT

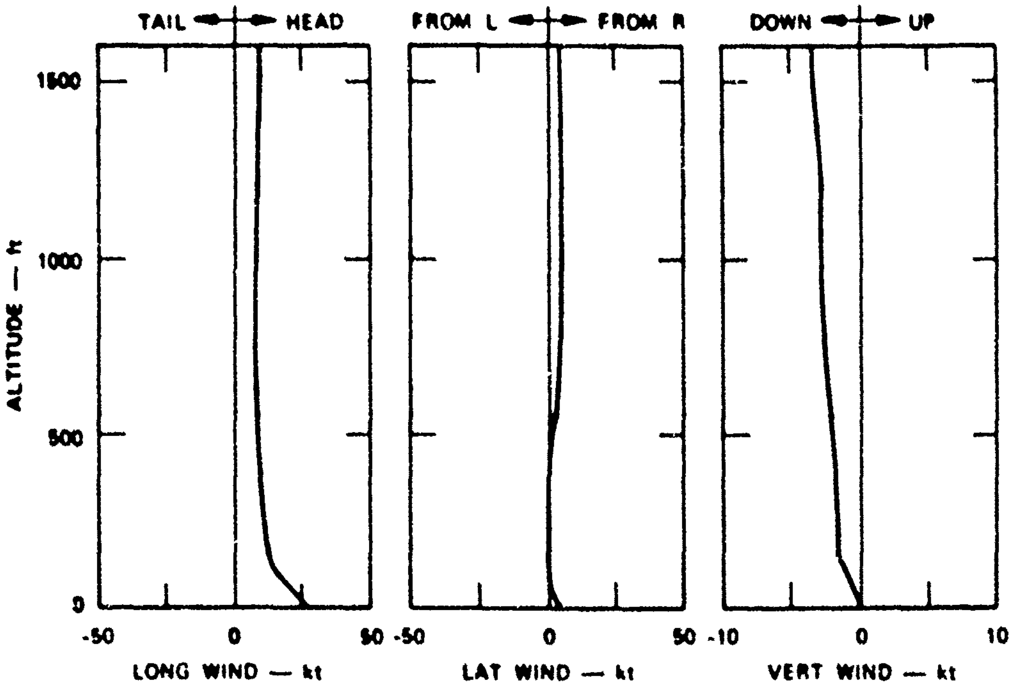


WIND PROFILE 13, TAKEOFF WITH 6° CLIMBOUT



WIND PROFILE 14, TAKEOFF WITH 6° CLIMBOUT

Meteorological Type. Cold Front



Source Tower measurements

WIND PROFILE 15, TAKEOFF WITH 6° CLIMBOUT

Appendix B

SENSOR MODELS

Wind shear and its effects on aircraft are dynamic phenomena, so the performance of an aiding device or instrument will depend on the accuracy and dynamic behavior of the sensors that supply the information on which the device operates. Accuracy can usually be assessed in a simulation by including random noise terms. The fundamental parameters governing dynamic response are time delay (or update time) and smoothing time (or bandwidth). This appendix shows the models used in the DC-10 simulator to accept the ideal computed values and produce simulated measuring device outputs. The outputs of the sensor models drove the corresponding instruments and displays used in the test.

The models are shown in block diagram form with the linear transfer functions given in terms of Laplace transforms with "s," the complex frequency variable. It should be remarked that capacity limitations in the simulation computer allowed no more than two independent random number generators for simulation of noise terms.

The following variables were used directly—that is, the "sensed" quantity was identical to the ideal quantity computed for the simulated airplane:

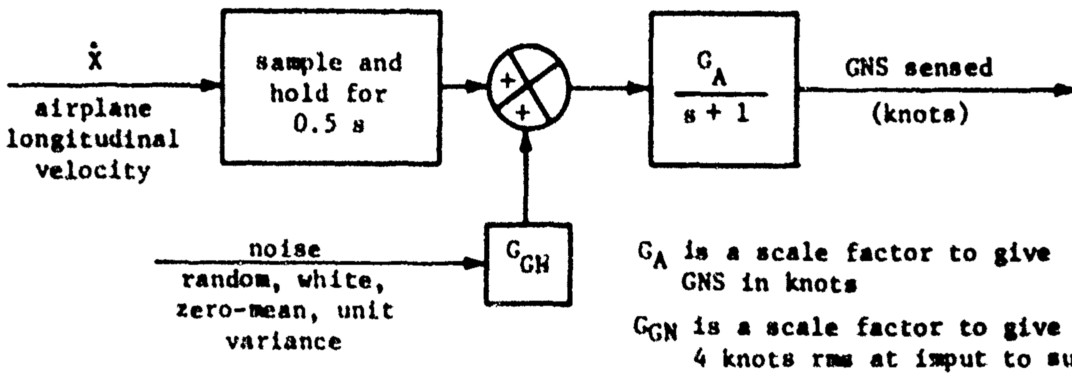
- Pitch angle, θ, positive up (deg)
- Longitudinal wind at near end of runway, V_{WXgnd}, tailwind positive (knots)
- Longitudinal wind at far end of runway, V_{WXfar}, tailwind positive (knots)

The following sensed quantities were computed by a Douglas model of a 3° ILS:

- Glide slope deviation, ΔGS, positive high (deg)
- Localizer deviation, ΔLOC, positive right (deg).

The other quantities were computed as shown in the models depicted below.

Ground Speed:

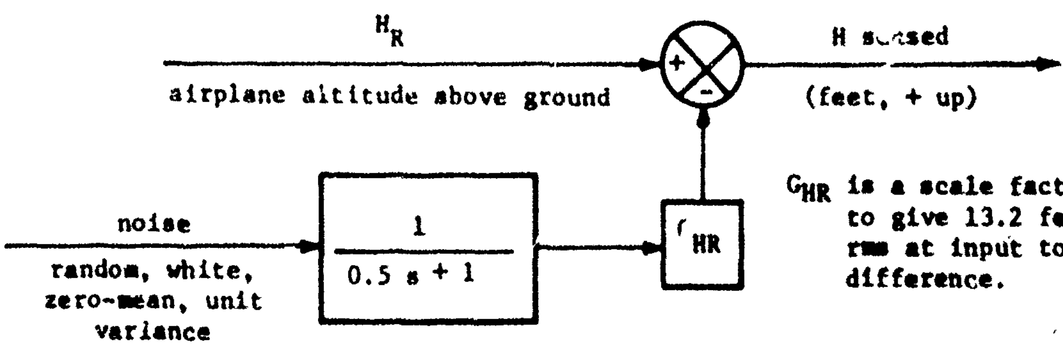


G_A is a scale factor to give GNS in knots

G_{GN} is a scale factor to give 4 knots rms at input to sum.

Note: This model for ground speed can represent a device such as a measurement using phase comparison or Doppler shift of a tone modulated onto one of the ILS carriers.

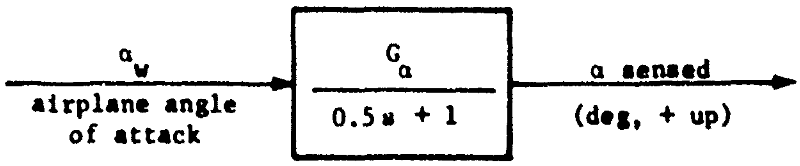
Height Above Ground:



G_{HR} is a scale factor to give 13.2 feet rms at input to difference.

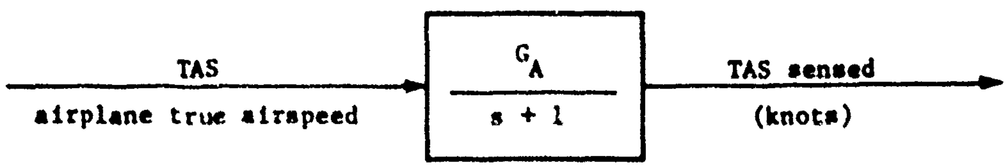
Note: This model is an approximate representation of the output of a radio altimeter on approach over comparatively level terrain with buildings positioned randomly (e.g., Denver, Colorado).

Angle of Attack:



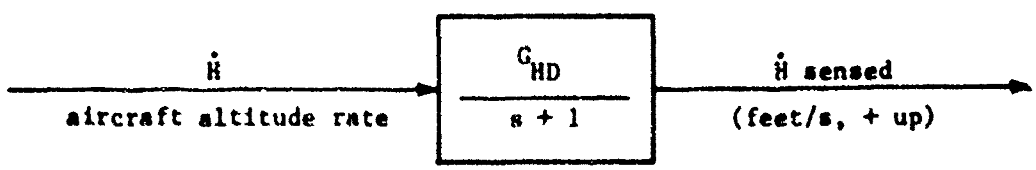
G_α is a scale factor to give α in degrees.

True Airspeed:



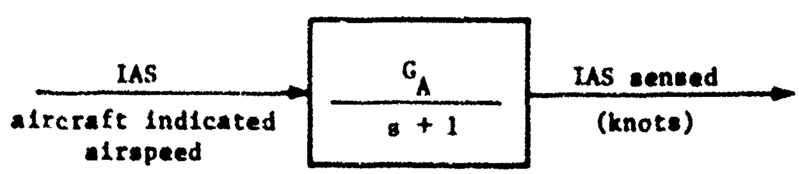
G_A is scale factor to give TAS in knots.

Vertical Velocity:



G_{HD} is scale factor to give $\dot{H}$ in ft/s.

Indicated Airspeed:



G_A is scale factor to give IAS in knots.

Appendix C

TECHNICAL DESCRIPTION OF RUN EVALUATION (MICROPROCESSOR) DISPLAY

A 20-character alphanumeric display was developed to provide information on the runway winds and the winds at the aircraft, to give warning of high or low speed, and to advise a go-around if the situation called for it. The operation of the unit and its set of messages are discussed in Section III-H. This appendix gives a technical review of the display's design and construction.

The message formats, the set of messages, and the algorithms were designed by W. H. Foy (SRI) with the help of G. J. Moussally (SRI) and W. O. Nice (BR). The microprocessor programming and hardware implementation work was led by M. G. Keenan and R. D. Daniel, with the support of D. W. Ellis, J. H. Priedigkeit and C. E. Wischmeyer, all of SRI.

Figure C-1 shows the hardware layout of the display and its associated equipment. The 12 analog data lines carried dc signals from the Sigma-5 simulation computer; the TOGA, "run reset" and "mission start" lines were binary logic signals also from the computer. The analog lines were multiplexed, sampled, and converted to digital data words by the A/D converter. A Motorola M6800 microprocessor was the central digital processor that made the calculations and controlled the displays. With it were a 2-kbyte read-and-write memory (RAM) and four programmable read-only-memory (PROM) chips each of 2 kbytes. The RAM held data values, results of calculations, and message codes; the PROMs held the routines and constant quantities. The microprocessor output port drove the lines to the two 20-character display units.

The logic that governed the display operation is diagrammed in the flowchart of Figure C-2, and the message types are summarized in Table C-1. At the start of an approach the airplane situation is calm, so the displays show the NR-FAR message indicating runway winds. During

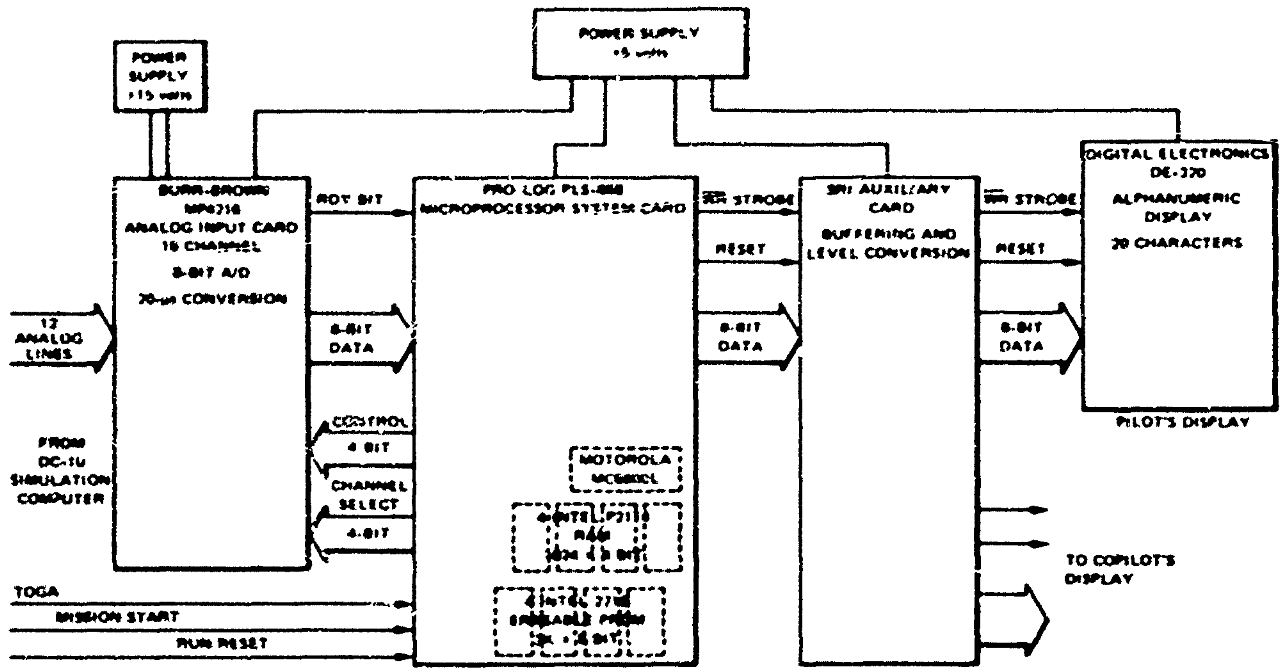


FIGURE C-1 MICROPROCESSOR ALPHANUMERIC DISPLAY

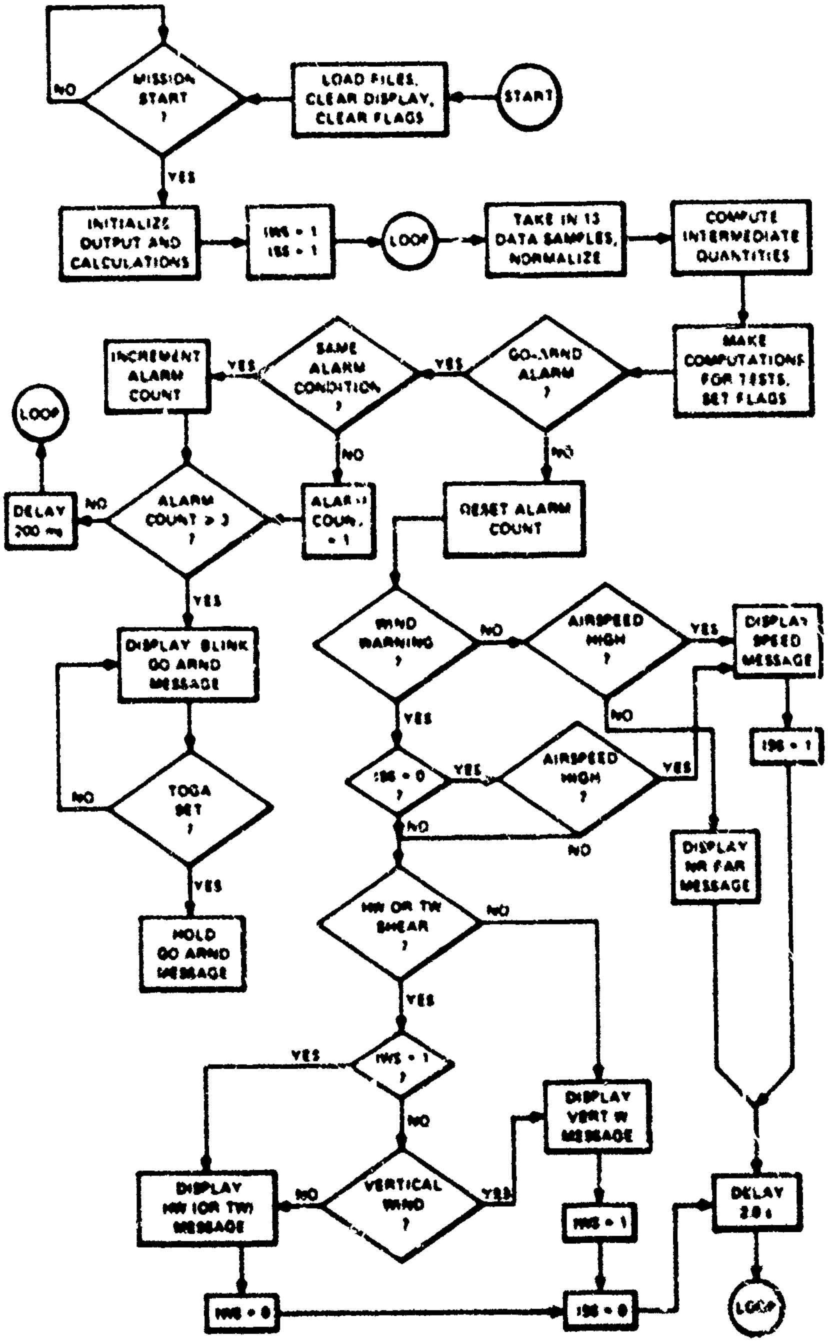


FIGURE C-2 DISPLAY LOGIC

Table C-1

MESSAGES ON RUN EVALUATION DISPLAY

Longitudinal winds along runway	
	NR HW 23K FAR TW 10K
Longitudinal wind shear	
	HW (or TW) DEC (or INC) SP LOSS (or GAIN) 33K/H
Vertical wind	
	VERT W UPDRAFT (or DOWNDRAFT) 21K
Airspeed warning	
	SPEED HIGH FOR FLAPS
Go-around advisories (airplane before runway threshold)	
	GO ARND UNDERSHOOT
	GO ARND ACCEL LACK
	GO ARND OFF TO RIGHT (or LEFT)
	GO ARND SPEED LOW
Go-around advisories (airplane across runway threshold)	
	GO ARND OVERSHOOT
	GO ARND DESCENT RATE

the approach, if a go-around is indicated, the main loop is exited, the appropriate GO-ARND message is blinked until the pilot responds by pushing the TOGA button, and then the message is held until the approach is terminated. If no go-around is advised, the routines test for "wind warning indicated?" and "speed high?"; if both these conditions occur, the ISS switch (Figure C-2) causes the SPEED message or a wind warning message to be put on the displays alternately on each pass around the loop. When a wind warning is indicated, the routines display a VERT W message if vertical winds greater than 5 knots are detected, or a HW(TW) INC(DEC) message if longitudinal wind shear greater than 8 knots per 100 feet of altitude change is estimated; if both occur, the IWS switch alternates the messages on the loop passes. In this way a GO-ARND condition takes top priority, and a SPEED or VERT W or wind-shear warning will override the NR-FAR message. The main loop will be exited if the run is terminated, indicated by a "run reset" signal.

Table C-2 lists the variables that were needed as inputs and the various quantities that were computed in order to determine the appropriate message to be displayed.

Table C-2

QUANTITIES IN DISPLAY COMPUTATIONS

Inputs	
Pitch angle	θ positive up (deg)
Angle of attack	α positive up (deg)
True airspeed	TAS (knots)
Ground speed	GNS (knots)
Altitude above runway	H positive up (feet)
Vertical velocity	$\dot{H}$ positive up (feet/s)
Longitudinal wind at runway near end	VWX_{gnd} positive tailwind (knots)
Longitudinal wind at runway far end	VWX_{far} positive tailwind (knots)
Localizer deviation	ΔLOC positive to right (deg)
Longitudinal displacement	X positive in direction of approach, X = 0 at glidepath intercept (feet)
Acceleration demand	A_{dem} (knots/s)
Indicated airspeed	IAS (knots)
Constants	
Air density	ρ (slug/foot^3)
Acceleration of gravity	g_o (feet/s^2)
Runway length	l_r (feet)
Nominal glideslope angle	GSA (deg)
Weight of airplane	W (lb)
Reference wing area	S (feet^2)
Drag coefficients	C_{DM}, C_{LREF}

Table C-2 (Concluded)

Lift coefficients	C_{LO}, $C_{L\alpha}$, C_{LMAX}
Maximum available thrust	T_m (lb)
<u>Computed Quantities</u>	
Air-mass flight-path angle	γ_a (deg)
Longitudinal wind at airplane	V_{WX} (knots, + tailwind)
Vertical wind at airplane	V_{Wh} (knots, + up)
Estimated height loss on go-around	ΔH_{go} (feet)
Distance to stop on runway	ΔX_{run} (feet)
Acceleration margin	ΔA (knots/s)
Clearance altitude	H_{obs} (feet)
Allowable descent rate at landing	V_{fh} (feet/s)
Longitudinal wind shear	ΔV_W (knots/foot)

The calculations may be summarized as follows:

- General--winds

  $$\gamma_a = \theta - \alpha$$

  $$V_{WX} = (GNS) - (TAS)\cos\gamma_a$$

  $$V_{Wh} = \dot{H} - (TAS)\sin\gamma_a$$

  $$\Delta V_W = \frac{V_{WX} - VWX_{gnd}}{H}$$

- Estimated height loss on go-around

  ΔH_{go} = approximation dependent on $\dot{H}$, TAS, V_{Wh}, W, T_m, ρ; developed from the differential equations of motion.

- Distance from present position to touchdown (past runway threshold)

  $$\Delta X_{TD} = \begin{cases} -H(GNS)/\dot{H} \text{ when } \dot{H} < -1 \\ \frac{1}{6}H(GNS) \text{ when } 0 \geq \dot{H} \geq -1 \\ (\frac{3}{2} + \frac{1}{4}\dot{H} + \frac{1}{6}H)(GNS) \text{ when } \dot{H} > 0. \end{cases}$$

- Distance from present position to stop on runway

  $\Delta X_{run} = \Delta X_{TD} + \Delta X_{stop}$

  with ΔX_{stop} = the wet-runway stopping distance, dependent on GNS, VWX_{gnd}, VWX_{far}, W, and ρ; developed from straight-line interpolations in the table of braking distances.

- Acceleration margin

  $\Delta A = A_{cap} - A_{dem}$

  with A_{cap} = 1.0 knots/s.

- Minimum clearance altitude

  $$H_{obs} = \begin{cases} (-X - 1750) \tan 1.15° & \text{if } x \leq -1750 \\ 0 & \text{if } x > -1750 \end{cases}$$

  where X = -1000 feet is the runway threshold.

- Maximum safe descent rate (past runway threshold)

  $V_{fh} = \sqrt{100 + 8\,(H)}$

When these quantities were computed, the program was then ready to test for the following alarm and warning conditions:

- Go-around alarm--If the airplane is before runway threshold (X < - 1000), count the indicated GO ARND alarm condition when:

$H - \Delta H_{go} < H_{obs} + 40$	Undershoot
$\Delta A < 0$	Acceleration lack
$\Delta LOC > 0.32°$	Off to right
$\Delta LOC < -0.32°$	Off to left
IAS < 116 knots	speed low.

  If the airplane has crossed the runway threshold ($X \geq -1000$), count the indicated GO ARND alarm condition when:

$X + \Delta X_{run} + 1000 > l_r - 300$	Overshoot
$\dot{H} < -V_{fh}$	Descent rate.

- Wind warning--Generate a wind warning with the indicated message when:

$\lvert \Delta V_W \rvert > 0.08$ knots/ft	HW (or TW) shear
$\lvert V_{WH} \rvert > 5$ knots	Vertical wind.

- Airspeed warning--Generate a SPEED HIGH message when:

  IAS > 170 knots   Speed high for flaps.

These tests contained several "alarm limits" and "safety margins" that depend on the characteristics of the simulated DC-10 airplane and were chosen empirically. Some analytical work would be required if this display were to be adapted to another type of aircraft.

As usual in a microprocessor job, writing the program code constituted a major part of the effort. The M6800 is organized to handle 8-bit bytes. An 8-bit input data sample could fit in one byte, but many more significant bits were required to get the necessary accuracy in the intermediate calculations. Therefore a special floating point data-word format was used: one byte held the exponent and the next byte held the mantissa. Special mathematical routines were written to manipulate these data words. Various message formatting, input/output and computation routines were also required. In all, the programming effort involved writing and checking out some 59 separate routines, as listed in Table C-3. Much of this program development was done on a time-sharing computer service that provided an M6800 development package.

The justification for undertaking this development is that the programming job is a one-time task. With it completed, the cost of any additional display unit is the cost of the hardware only. As Table C-4 shows, the hardware in the microprocessor display unit for the simulator came to a total of $2156.

Table C-3

MICROPROCESSOR PROGRAMS

Name	Purpose	Number of Bytes
Executive and Computational Routines		
EXEC	Executive routine for run evaluation display	240
WSTST	Test for wind shear and vertical winds	227
GACUND	Test for go-around because of undershoot	79
GACACC	Test for go-around due to acceleration margin	244
GACR	Test for go-around due to right deviation	46
GACL	Test for go-around due to left deviation	46
GACSPD	Test for go-around due to low airspeed	46
GACOVR	Test for go-around due to predicted overshoot	102
GACDRT	Test for go-around due to high descent rate	63
GAFGST	Set flags for the go-around conditions	9
ASTEST	Test for airspeed too high for flaps	33
FLGCLR	Clear all condition flags	31
INCAL	Initialize flags, messages, and computations	30
X1X	Compute distance from runway threshold	61
NFWIND	Put the variable numbers into NR-FAR message	57
KTOFS	Convert knots to feet per second	15
SLCON	Store constants for the landing situation	48
GAVAL	Issue go-around advisory only after three consecutive alarms	15
WINDM	Select proper wind shear message	49
CONVXC	Convert X-coarse input to floated number	39
GORNDM	Select proper go-around message	55
STEXP	Store exponents for A/D conversions	32
INS4	Execute 4 consecutive INS instructions	33
SLIM	Store constants for test limits	20
GENCAL	Compute γ_a, vertical wind and wind shear	210
LANDCO	Compute distance to stop, clearance altitude, maximum descent rate	328

Table C-3 (Continued)

Name	Purpose	Number of Bytes
HLGAM	Compute height loss on a go-around	881
XSTOP	Compute stopping roll distance on runway	283
	Input/Output Routines	
OCINIT	Initialize for character output	10
OCDISP	Put out a 20-character message to displays	63
OCCLD	Clear the characters of the displays	13
OCRITE	Pass alphanumeric characters to displays	14
DLY1S	Delay for 1 s	16
D100MS	Delay for 100 ms	13
DLY1MS	Delay for 1 ms	8
TOGA	Service the TOGA interrupt	5
ATOD	Accept inputs from A/D converter	67
MISHUN	Service the mission-start interrupt and set flag	7
EXLOAD	Transfer exponent file from ROM to RAM	38
ASDID	Add bias values to the inputs	99
MSGF	Store the characters for the messages	340
MLOAD	Transfer message file from ROM to RAM	38
HXDSP	Put 2 hex characters from A register on display	43
MSAME	Check current message to see if different from last	39
DIAG	Diagnostic routine for the display	155
DUMP	Dump the memory on the display	63
VECT	Store the reset and interrupt vectors	8
	Mathematical Routines	
ADSUB	Add or subtract two 16-bit fixed-point numbers	77
ABS	Take absolute value of 16-bit fixed-point number	65
FPMULT	Floating-point-multiply two floated numbers	215
FPADS	Add/Subtract two floated numbers	148
SINTAN	Compute sine and tangent for a floated number	77
INV	Invert a floated number, 1/X	125

Table C-3 (Concluded)

Name	Purpose	Number of Bytes
SQRT	Take the square root of a floated number	181
FPNOR	Normalize an unnormalized floated number	95
FPCMP	Compare two floated numbers	42
COSDEG	Compute the cosine of a floated number in degrees	85
ARCTAN	Convert an arctangent to degrees	60
FP2I1	Convert floated number to a 1-byte positive integer	23
I2AS2	Convert a 1-byte positive integer to ASCII code	35

Table C-4

LIST OF MATERIAL IN DISPLAY

Item	Number	Unit Cost	Amount
Intel Corp.			
2716 EPROM	4	$ 62.50	$250.00
2114 RAM	2	35.00	70.00
Burr-Brown Research Corp.			
MP4216 A/D card	1	195.00	195.00
Pro-Log Corp.			
PLS-868 microcomputer card	1	265.00	265.00
CR-5A card cage	1	72.00	72.00
P562 utility card	1	22.50	22.50
P560 card extender	1	31.50	31.50
Digital Electronics Corp.			
DE/320 alphanumeric display	2	350.00	700.00
Abbott Laboratories			
Z5T10 power supply	1	250.00	250.00
Power supply ± 15 volts	1	50.00	50.00
Misc. hardware and parts			250.00
Total			$2156.00

Appendix D

APPROACH AND LANDING PERFORMANCE SCORING

Evaluation of the performance of any system offered as an aid to the pilot in coping with wind shear is a complex matter. Any objective measure applied to simulation runs will be influenced by pilot proficiency as well as system utility, so the evaluator must average over several pilots. Each simulated approach can end with a touchdown or a go-around, and the merit of these responses will depend on the situation --the system/pilot should be able to make a successful landing when the wind shear is of low severity, but a go-around is appropriate with a high-severity profile. However, it would surely be an unrealistic and inept exercise to test against high-severity winds only, and let the system/pilot make nothing but go-arounds. Further, it has appeared in previous wind-shear simulation trials that the most difficult situation for a go-around advisory subsystem is presented by a wind-shear profile of moderate severity. Thus it follows that the test should include a mix of wind profile severities, and system performance should be marked down for go-arounds on low and moderate profiles.

With these considerations we designed a test for each system/pilot that involved two low-severity profiles, one moderate and two high. A system performance score, ranging in value from +10 to -10 points, was assigned to each data run in accordance with the scheme presented in Table D-1. Note that four possible approach outcomes are distinguished and that the number of points assigned to each outcome is determined by the severity of the wind-shear profile and the action of the go-around advisory system. A fully acceptable outcome, earning 10 points, was recorded for either a within-limit landing, when no go-around advisory was displayed, or for any successful go-around against a high-severity shear. Less than 10 points were earned for successful go-arounds on low and moderate severity shears because these conditions have been

Table D-1

SYSTEM PERFORMANCE SCORES FOR ALTERNATIVE
APPROACH OUTCOMES AND WIND-SHEAR SEVERITY LEVELS

Approach Outcome	Wind Shear Severity		
	Low	Moderate	High
No go-around advisory			
-Touchdown within limits*	+10	+10	+10
-Touchdown outside limits	-10	-10	-10
-Successful go-around	- 5	+ 2	+10
-Unsuccessful go-around†	-10	-10	-10
Go-around advisory			
-Touchdown within limits	‡	‡	‡
-Touchdown outside limits	‡	‡	‡
-Successful go-around	- 5	+ 2	+10
-Unsuccessful go-around	-10	-10	-10

*Touchdown limits are given in Table D-2.

†Aircraft contacts ground during go-around attempt (not within touchdown limits).

‡Invalid run because contrary to test procedure; event recorded for consideration as "false" advisory. Run was repeated.

shown to be negotiable by most pilots in earlier simulation studies; in effect, the system is penalized for unnecessary go-around advisories or "nuisance alarms."

Out-of-limit landings and unsuccessful go-arounds were regarded as very hazardous outcomes or outright crashes and were assigned a score of -10. An unsuccessful go-around was recorded when the aircraft contacted the ground during the attempt; this condition does not include go-arounds converted to a successful landing (within-limit touchdown) or safe touch-and-go maneuvers. The baseline system did not have a mechanism for advising go-around, so its runs were scored with only the "no advisory" part of Table D-1. The aiding systems tested did include go-around advisories and the pilot was asked always to execute a go-around when advised; if he did not, the run was not scored and was repeated. The circumstance where the aiding system did not issue a go-around advisory but the pilot decided to go around is somewhat anomalous --is it a system failure ("missed alarm") or is it due to poor approach management? As it turned out, this condition did not occur, so the question did not have to be answered.

The limiting values on airplane touchdown position, velocities, and attitude taken to define "within-limit" landings are given in Table D-2. All these are related directly to DC-10 landing specifications, with one exception--the DC-10 limit on touchdown descent rate is 10 feet/s while the limit we used was 14. This change was made because experience in the simulator showed that hard landings occurred much more often, even with no wind, than would be expected in actual operations. The high-descent-rate landing would appear to be an artifact of the simulation and its visual scene.

Table D-2

LANDING OUTCOME--TESTS FOR WITHIN LIMITS

Touchdown position
Across runway threshold
Touchdown before computed stopping distance predicted overshoot for far end of runway
Lateral deviation from centerline: $\pm$ 50 feet
Touchdown velocities
Rate of descent: < 14 feet/s
Lateral speed: < 15 feet/s
Touchdown attitude
Pitch angle: $\leq$ 13 deg, $\geq$ 0 deg
Roll angle: $\pm$ 9 deg

Another characteristic of a simulation exercise like these tests is that perfect performance is not to be expected. Our experience has shown that even with no wind, some 10% of the landings will be out of limits. In the Table D-2 scheme, this implies that of every 10 no-wind runs, 9 would be scored +10 and 1 would get -10, for an average score of 8.0. This represents the expected value of a score for top performance, equal to a 90-percent success rate.

As a final note on the performance score, it should be emphasized that the "system performance" necessarily includes the effects of aircraft performance capabilities and pilot performance of the approach management task as well as the influence of the experimental aiding systems. Thus, all of these effects and their interactions are reflected in the system performance score. However, since the aircraft, pilot, and environmental conditions (wind profiles, weather, etc.) were the same for all of the test systems, their effects are a common factor and the effect of the aiding system can be isolated and assessed by comparisons with baseline performance.

Appendix E

PRECISION-APPROACH TEST: QUESTIONNAIRES AND RESULTS FOR TEN SUBJECT PILOTS

GENERAL

1. For baseline, do you consider that it will solve the wind shear problem?

No solution	5
Basis for potential solution	5
Solution	0

2. For systems 4 and 6, assuming that each can be implemented at reasonable cost, do you consider that it will solve the wind shear problem?

	4 MFD/ΔA	6 GNS/RED
No Solution	0	0
Basis for potential solution	8	7
Solution	2	2
Uncertain	0	1

3. I think the wind shear profiles used in the simulation were:

About right	4
Very realistic	5
Much too severe	1
I have never seen anything like them	0

4. Was the simulation:

Very good	4
Good	6
Poor	0
Completely unrealistic	0

5. Have you ever used vertical tape type instruments before?

Yes	6
No	4

6. If I could choose I would have:

Vertical tape instruments	4
Dial needle type instruments	6

GROUND SPEED

1. Would you like to know your ground speed on final approach?

Yes	10
No	0
Don't care	0

2. As far as I am concerned I think the ground speed concept for aiding in detecting and flying in or avoiding wind shear should be:

Taught to all pilots	10
Forgotten	0

3. Do you believe the concept of flying a minimum ground speed as well as a minimum indicated speed is?

Excellent	9
No good	0
Neutral	1

4. After some experience with the two-needle display do you consider it:

Practical	10
Impractical	0
Nuisance	0

5. Did the two-needle display ever confuse you?

Yes	2
No	8

6. Which presentation of ground speed did you prefer?

Two needle	7
Kollsman vertical tape	3
None	0

7. The automated dual referenced F/S used in these ground speed experiments is

Greatest thing since Cracker Jack	6
Helps at times	4
Is of no value	0

FAST/SLOW

1. My airline has the F/S system in some of its planes.

Yes	9
No	0
Uncertain	1

2. When I have a working F/S on my ADI I use it:

As my primary speed control	3
Use it secondarily to the IAS	6
Uncertain	1

3. My opinion of the normal F/S indicator is:

Think it is excellent	8
Never use it even when available	0
Think it is superfluous	0
Uncertain	2

4. Having the speed control on the ADI such as you have used here is:

Excellent idea	8
OK	1
No value	0
Uncertain	1

MODIFIED FLIGHT DIRECTOR

1 In my opinion the modified flight director as compared with the standard flight director is:

Better	10
Worse	0
Same	0

2. Flying the approaches in the most severe conditions would you rather have the:

MFD	9
Standard FD	1

3. In your opinion did the pitch bar on the MFD call for action that you consider unsafe?

Yes	0
No	10

4. Were you able to fly this MFD as precisely as you would like?

Yes	5
No	4
Uncertain	1

5. I would like to have the modified flight director in my airplane.

Never	0
At all times	4
Only for tough turbulent approaches	5
Uncertain	1

6. Is the Bank steering bar on the MFD too active?

Yes	1
No	9

7. Is the pitch bar on the MFD too active?

Yes	3
No	7

8. Was the MFD smooth enough to be used in airline day to day operation?

Yes	6
No	3
Uncertain	1

9. I would like to have a switch that allowed me the option to use or not use the MFD

Yes	7
No	1
Uncertain	2

10. Did it help you to make a more precise approach?

Yes	10
No	0

GO-AROUND

1. How far below your reference or V2 speed do you feel you can safely go to effect a satisfactory go around?

5 knots	0
10 knots	3
15 knots	1
20 knots	0
Stick shaker	6
None at all	0

2. The pitch angle required to satisfy the FD during the aided go-arounds was:

Much greater than I would normally use	2
Seemed about right	5
Somewhat greater than I felt comfortable with	1
Uncertain	2

3. I think knowing the status of my AOA as displayed on the F/S during go-arounds:

Is very important	6
Nice supplementary information	1
Not important to me	0
Uncertain	3

4. The AOA displayed on the F/S to aid you in the go-arounds was:

Very helpful	4
Helped somewhat	2
Of no value	0
Uncertain	4

5. In general, I like having the FD help me perform the go-around maneuver.

Yes	10
No	0

6. The modified go-around command on the pitch steering bar was:

Very helpful	10
Helped somewhat	0
Didn't help	0

ACCELERATION MARGIN

1. Did you believe the acceleration margin light:

All of the time	3
Most of the time	7
Some of the time	0
Not at all	0

2. The acceleration margin is a good clue to power needs.

Yes	9
No	1

3. The acceleration margin instrument was

Easily within my scan	5
Saw it only occasionally	5
Wasn't able to use it	0

4. I used the acceleration margin scale to

Monitor thrust needs	9
As a thrust control instrument	0
Didn't use it	1

5. The acceleration margin light commanded a go-around:

Too soon	0
Soon enough	9
Too late	0
Uncertain	1

6. I would like to have an acceleration margin instrument in my cockpit.

Yes	8
No	1
Uncertain	1

RUN EVALUATION DISPLAY

1. The best information given to me by the RED was:

Wind shear information	0
Ground wind information	5
Speed information	0
Go-around advisories	5

2. How did you use this display?

Had it monitored by the 1st officer	9
Watched it myself	0
Paid no attention to it	0
Uncertain	1

3. The best thing about this display was:

Information about the winds	1
Advising me to go around	8
Uncertain	1

4. When it comes time to abandon any approach I would prefer:

To be aided in my decision by a black box	6
Prefer my own interpretation from standard instruments	1
Uncertain	3

5. I would like to have the RED Display in my plane:

Yes	6
No	2
Uncertain	2

6. The RED Display was:

Very helpful	2
Helpful at times	7
Distracting	0
Uncertain	1

Appendix F

NON-PRECISION APPROACH TEST: QUESTIONNAIRES AND RESULTS FOR TEN SUBJECT PILOTS

OPERATIONS

1. Rate the difficulty of executing non-precision approaches (NPA) compared to precision approaches:

	EASY 1	2	3	4	5	6	7	8	9	10
Precision	4	3	1	1	1					
Non-Precision					3	2	1	1	2	1

2. Approximately how many NPA's did you make in 1978?

Aircraft 17.5 (average)
Simulator 4.5 (average)

3. If you had a choice, which type NPA would you select:

No vertical guidance	3
No lateral guidance	0
Uncertain	7

Remarks: This was a bad question.

4. During normal operations, do you use your FD to its full capability in NPA?

Usually	6
Always	3
Never	1

5. When executing NPA, what is the maximum rate of descent you will tolerate between out marker and MDA?

2000 ft/min	1
1500	3
1200	4
1000	2

6. Do you try to reach MDA well before MAP?

Yes	9
No	0
Uncertain	1

7. The most difficult phase of NPA is:

Preparation prior to descent fix (checklist, speed reduction, flap extension, etc.)	1
Descent from fix to MDA	1
Maintaining altitude at MDA while approaching VDP or MAP	3
Landing maneuver after runway is sighted	5

8. Which of the following is most critical in NPA:

Preparation prior to descent fix	1
Speed control	0
Altitude control	4
Landing maneuver	5

9. Rate the following in order of importance in flying NPA:

Visual descent point	1.94 (average)
VASI	1.94 (average)
Flight director	2.11 (average)

10. Your opinion of the synthetic glide slope, please:

Extremely valuable	3
Of some assistance	0
Lessened workload appreciably	4
Turned NPA into precision approach	3
Had no confidence in it	0

11. Would you like to have the acceleration margin gauge and light during line operations?

Yes	10
No	0

12. Was the Run Evaluation Display helpful during NPA?

No	1
Very little value, increases workload	1
Not enough training	1
Somewhat	1
Yes, when data called out by copilot	3
Yes	3

GENERAL

1. For baseline, do you consider that it will solve the wind shear problem?

No solution	6
Basis for potential solution	4
Solution	0

2. For systems A and B or C, assuming that each can be implemented at reasonable cost, do you consider that it will solve the wind shear problem?

	A MFD/ΔA	B or C GNS/MF/R
No solution	1	1
Basis for potential solution	5	6
Solution	3	2
Uncertain	1	1

3. I think the wind shear profiles used in the simulation were:

About right	3
Very realistic	6
Much too severe	0
I have never seen anything like them	1

4. Was the simulation

Very good	6
Good	4
Poor	0
Completely unrealistic	0

5. Have you ever used vertical tape type instruments before?

Yes	4
No	6

6. If I could choose I would have

Vertical tape instruments	3
Dial needle type instruments	5
Uncertain	2

GROUND SPEED

1. Would you like to know your ground speed on final approach?

Yes	10
No	0
Don't care	0

2. As far as I am concerned I think the ground speed concept for aiding in detecting and flying in or avoiding wind shear should be:

Taught to all pilots	10
Forgotten	0

3. Do you believe the concept of flying a minimum ground speed as well as a minimum indicated speed is:

Excellent	10
No good	0
Neutral	0

4. After some experience with the two-needle display do you consider it?

Practical	9
Impractical	0
Nuisance	0
Uncertain	1

5. Did the two-needle display ever confuse you?

Yes	1
No	8
Uncertain	1

6. Which presentation of ground speed did you prefer?

Two-needle	5
Kollsman vertical tape	5
None	0

7. The automated dual referenced F/S used in these ground speed experiments is:

Greatest thing since Cracker Jack	5
Helps at times	5
Of no value	0

FAST/SLOW

1. My airline has the F/S system in some of its planes.

Yes	10
No	0

2. When I have a working F/S on my ADI I use it:

As my primary speed control	6
Use it secondarily to the IAS	4

3. My opinion of the normal F/S indicator is:

Think it is excellent	9
Never use it even when available	0
Think it is superfluous	0
OK as backup	1

4. Having the speed control on the ADI such as you have used here is:

Excellent idea	9
OK	1
No value	0

MODIFIED FLIGHT DIRECTOR

1. In my opinion the modified flight director as compared with the standard flight director is:

Better	10
Worse	0
Same	0

2. Flying the approaches in the most severe conditions would you rather have the:

MFD	10
Standard FD	0

3. In your opinion did the pitch bar on the MFD call for action that you consider unsafe?

Yes	0
No	10

4. Were you able to fly this MFD as precisely as you would like?

Yes	7
No	3

5. I would like to have the modified flight director in my airplane.

Never	0
At all times	8
Only for tough turbulent approaches	1
Uncertain	1

6. Is the Bank steering bar on the MFD too active?

Yes	1
No	9

7. Is the pitch bar on the MFD too active?

Yes	0
No	10

8. Was the MFD smooth enough to be used in airline day-to-day operation?

Yes	9
No	1

9. I would like to have a switch that allowed me the option to use or not use the MFD.

Yes	4
No	6

10. Did it help you to make a more precise approach?

Yes	10
No	0

GO-AROUND

1. How far below your reference or V2 speed do you feel you can safely go to effect a satisfactory go-around?

5 knots	0
10 knots	2
15 knots	2
20 knots	0
Stick shaker	6
None at all	0

2. The pitch angle required to satisfy the FD during the aided go-arounds was:

Much greater than I would normally use	2
Seemed about right	6
Somewhat greater than I felt comfortable with	2

3. I think knowing the status of my AOA as displayed on the F/S during go-arounds:

Is very important	4
Nice supplementary information	2
Not important to me	0
Uncertain	4

4. The AOA displayed on the F/S to aid you in the go-arounds was:

Very helpful	4
Helped somewhat	1
Of no value	1
Uncertain	4

5. In general, I like having the FD help me perform the go-around maneuver.

Yes	10
No	0

6. The modified go-around command on the pitch steering bar was:

Very helpful	9
Helped somewhat	1
Didn't help	0

ACCELERATION MARGIN

1. Did you believe the acceleration margin light:

All of the time	7
Most of the time	3
Some of the time	0
Not at all	0

2. The acceleration margin is a good clue to power needs.

Yes	10
No	0

3. The acceleration margin instrument was:

Easily within my scan	3
Saw it only occasionally	7
Wasn't able to use it	0

4. I used the acceleration margin scale to:

Monitor thrust needs	7
As a thrust control instrument	1
Didn't use it	0
Anticipate the needs	2

5. The acceleration margin light commanded a go-around:

Too soon	0
Soon enough	10
Too late	0

6. I would like to have an acceleration margin instrument in my cockpit.

Yes	10
No	0

RUN EVALUATION DISPLAY

1. The best information given to me by the RED was:

Wind sheer information	0
Ground wind information	1
Speed information	1
Go-around advisories	8

2. How did you use this display?

Had it monitored by the 1st officer	10
Watched it myself	0
Paid no attention to it	0

3. The best thing about this display was:

Information about the winds	1
Advising me to go-around	9

4. When it comes time to abandon any approach I would prefer:

To be aided in my decision by a black box	10
Prefer my own interpretation from standard instruments	0

5. I would like to have the RED Display in my plane.

Yes	5
No	2
Uncertain	3

6. The RED Display was

Very helpful	4
Helpful at times	4
Distracting	1
Uncertain	1

Appendix G

TABULATION OF NUMBER OF APPROACH-AND-LANDING OUTCOMES

Approach and Severity	Go-Arounds		100-ft Window		Touchdown		Total Runs
	Successful	Unsuccessful	In-Limits	Out-of-Limits	In-Limits	Out-of-Limits	
<u>Precision Approach</u>							
BL							
Low Severity	7	--	8	5	7	6	20
Moderate	7	--	3	--	1	2	10
High Severity	8	6	3	3	3	3	20
MFD/ΔA							
Low Severity	2	--	18	--	14	4	20
Moderate	5	--	4	1	4	1	10
High Severity	17	--	2	1	3	--	20
GNS/RED							
Low Severity	9	--	8	3	8	3	20
Moderate	4	--	2	4	2	4	10
High Severity	15	--	2	3	2	3	20
<u>Non-Precision Approach</u>							
BL							
Low Severity	11	--	3	6	6	3	20
Moderate	5	--	1	4	3	2	10
High Severity	9	3	2	6	6	2	20
MFD/ΔA							
Low Severity	5	--	14	1	14	1	20
Moderate	5	--	3	2	5	--	10
High Severity	15	1	4	--	4	--	20
GNS/MP/R							
Low Severity	7	--	5	4	7	2	16
Moderate	1	--	5	2	4	3	8
High Severity	7	--	7	2	8	1	16

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